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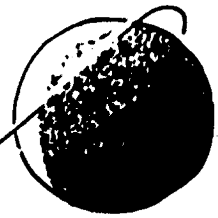

COMPARATIVE EVALUATION OF PAPER HONEYCOMB TESTING

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W. L. GUYTON, GARLAND SPRETZ

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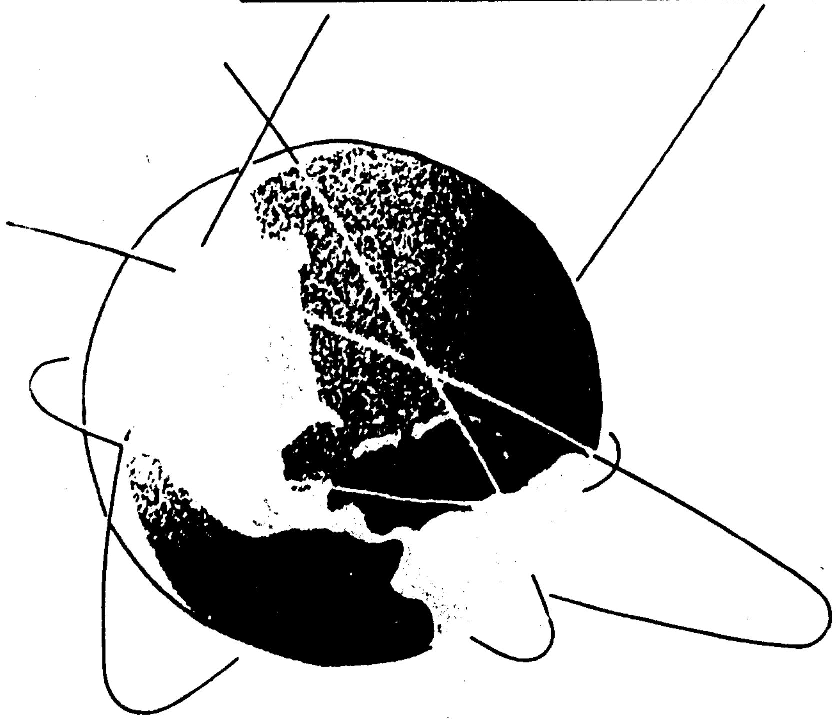
EMRL TR 1013 MARCH 1967



ENGINEERING MECHANICS RESEARCH LABORATORY

THE UNIVERSITY OF TEXAS · AUSTIN, TEXAS

EMRL TR 1013

COMPARATIVE EVALUATION OF PAPER HONEYCOMB TESTING

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U. S. Army Natick Laboratories

Air Drop Engineering Division

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Engineering Mechanics Research Laboratory

The University of Texas

Austin, Texas

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INTRODUCTION

The purpose of this report is to compare the results of honeycomb tests conducted by the Engineering Mechanics Research Laboratory with results from honeycomb tests conducted by the Natick Laboratories. The data used for comparison were obtained from parallel test programs conducted by the two facilities. Four 16 in. x 18 in. test samples each were cut at the Natick Laboratories from 3 ft x 8 ft honeycomb panels selected at random from a contractor's shipment. This provided two ostensibly identical sets of dual samples. One set was retained at Natick and tested there. The other was shipped to the Engineering Mechanics Research Laboratory at The University of Texas and tested there. Two different honeycombs were included in the program. One identified as Honeycomb X, has a crushing strength of approximately 6300 psf, and the other identified as Honeycomb Y, has a crushing strength of approximately 12,000 psf.

The raw data from the Natick Laboratories test series were furnished to the Engineering Mechanics Research Laboratory along with Natick's own evaluation of these data. The Natick results plus an evaluation of EMRL's test data in which hand fitting of acceleration records was employed provide the first set of results for comparison. As a part of the program, EMRL also evaluated the Natick raw data. Because of the form of these data, however, the usual hand smoothing data reduction methods were not satisfactory. Consequently, a new method was devised which uses a computerized mathematical curve fitting procedure. This procedure was used to evaluate the Natick data and to re-evaluate the EMRL data. The EMRL and the Natick results obtained by both data reduction methods are compared.

A brief description of the experimental procedure used for the EMRL tests is presented and the data reduction techniques are discussed in detail. The report includes tables of the results obtained from the raw data plus statistical comparisons of these sample results. A brief discussion is given of a method for statistically inferring some knowledge of the properties of the entire honeycomb shipment from which these samples were selected. A detailed discussion of the EMRL testing techniques is included in Appendix I and stress-strain curves for all tests made are included in Appendix II.

COMPARATIVE TEST PROGRAM

Experimental Procedure

The test samples Honeycomb X 1-A through 10-B and Honeycomb Y 1-A through 6-B received by the Engineering Mechanics Research Laboratory were tested in two separate drop series using the EMRL 85 foot drop facility. A specially designed streak camera[1*] is used to record the instantaneous height of the mass during impact. Strain as a function of time is determined from this record. The instantaneous stress in the honeycomb is directly proportional to the acceleration of the impacting mass. This acceleration is measured as a function of time with a Statham** 500 g fluid damped accelerometer, an oscilloscope and a polaroid camera. To reduce oscillations in the acceleration record, a 600 cps low pass filter is used in the acceleration measuring circuit. The stress-time and strain-time records are then converted to stress-strain curves using the "hand fitting method" and later, for comparison, the "computerized least squares method."

A more detailed discussion of the EMRL experimental drop test procedures is given in Appendix I. The test procedures used by Natick are described in Reference 2.

Data Interpretation

By definition, the strain in the honeycomb specimen is the ratio of the amount the specimen has been crushed to the original thickness. These measurements can be taken directly from the streak record which is a smooth continuous photographic curve indicating absolute height of a small light mounted on the falling mass. The strain determined from this curve will be a very good approximation to the average strain in the specimen, provided the light is mounted near the center of gravity of the mass and the impact is reasonably plane. Assuming that these two conditions are met, measurement of

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*Superscript numerals indicate references given in the List of References.

**Mod. A5-500-350.

strain from streak records is a straightforward process requiring no interpretive decisions on the part of the data analyzer.

Unfortunately, deduction of the stress within the honeycomb specimen from the acceleration-time record obtained in the above manner is not so straightforward. Because the accelerometer is mounted on the impacting mass, the acceleration measured is actually that of a mechanical body that has its own resonant frequencies and natural modes of vibration. In addition, because the accelerometer is also a mechanical body and its internal parts vibrate naturally upon impact, its electrical output is not always proportional to the acceleration of the impacting mass.

The effect of the presence of these two additional variables is thought to account for the majority of the higher frequency oscillations that appear on the stress-time records. This appraisal is supported by observations of the appearance of acceleration records taken using impacting masses of various degrees of rigidity and accelerometers of varying natural frequency. Further support is obtained from the appearance of acceleration records obtained during tests of a new EMRL honeycomb tester now under development for Natick Labs.[3] Since the oscillations on the acceleration record apparently do not represent dynamic crushing stress properties of the honeycomb, the data analyzer is obliged to infer these properties from the record. On an idealized basis, average effects of the oscillatory motion of the mass and the accelerometer as mechanical bodies subjected to a step input in force are theoretically zero. Therefore, the logical step to use in reducing the data from the acceleration record is to replace the original oscillating curve with a curve that represents the average instantaneous acceleration of the impacting mass, reflecting as closely as possible the essential shape of the original curve and containing beneath it the same area as does the original curve. The electronic filter mentioned above is a physical method used for this averaging purpose. Oscillations that are still present in the record after filtering however, must be averaged by the data analyzer.

A second problem involved in obtaining stress-time properties from the acceleration-time record is due to the finite response times of physical systems. Because the accelerometer is a physical system, it requires a finite amount of time to respond to any changes in the velocity of the mass. The oscilloscope also has a time lag in its response to the signal input, and when the filter is included as part of the measuring circuit, the time lag is even greater. Consequently, though the crushing stress at the interface between the impacting mass and the honeycomb specimen may build up almost instantaneously at first contact, the measuring system will not be able to respond fast enough to indicate what has actually taken place. The stress will not build up instantaneously because the impact will never be exactly plane. The instrumentation will still lag somewhere behind the physical event however, regardless of the planeness of the impact. The measuring system time lag and the planeness of impact of the mass on the honeycomb specimen must therefore be taken into account when the initial rise of the stress-strain curve and initial value of crushing stress are determined. The true form of the stress-time curve at the instant of impact is therefore subject to an interpretation that must be made by the data analyzer.

Thus in order to make sound technical use of the information contained in the acceleration-time record and the streak record, some decisions must be made as to which properties indicated by the data are actually dynamic crushing stress properties of honeycomb. In particular, the analyzer must use his judgement to:

1. Fit an average curve to the oscillating acceleration-time record.

2. Determine how to represent the initial part of the stress-strain curve.

Data Reduction Methods

Two methods were used to reduce the raw acceleration-time and displacement time records obtained during test to the dynamic stress-strain properties of paper honeycomb. The required decisions about the form of the data were made for both methods.

Hand Fitting Method

Using the OSCAR* digital data reduction machine, stress-time points were read directly from the acceleration-time record. The points were chosen from the record in such a way that a replot produced a good reproduction of the original curve. At this point, an "average" curve was hand fitted to the data, using the guidelines outlined in the Data Interpretation section. The point at which this hand fitted curve intersected the initial rise of the stress-time record was specified as the dynamic yield stress point for the honeycomb.

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*Benson Lehner Company, Model J.

A typical record with a hand fitted average curve is shown in Fig. 1.

Strain-time points were obtained directly from the streak record, also using the OSCAR, and replotted on a larger scale. By selecting average stress and measured strain values corresponding to a given time after impact (indicated by the time scale on both plots) a dynamic stress-strain curve for the honeycomb under test was constructed. Figure 2 shows a typical hand fitted stress-strain curve (dotted line) superimposed over an actual point by point correlation of the original stress-strain data (solid line). As Fig. 2 indicates, the initial yield stress apparently does not occur until the honeycomb has been strained to over 5%. For a six inch specimen, 5% strain represents 0.3 inches, which is much more crushing than is actually required before the yield stress in the honeycomb is reached. In fact, the crushing stress is actually reached for values of strain much less tha 1%. The apparent strain of 5% is due to the time lag in the response of the measuring system and the lack of planeness in the impact. To more nearly indicate the true stress conditions during impact, therefore, the initial dynamic yield stress is considered to occur at zero strain, and the stress between zero strain and the indicated yield point is considered to be constant at the dynamic yield stress level as indicated by Fig. 2.

The energy absorbed to 70% strain in the honeycomb is obtained by measuring the area under the dynamic stress-strain curve from zero to 70% strain. The average crushing stress to 70% strain is obtained from:

(Avg. Crushing Stress to 70% Strain)

= (Energy Abs. to 70% Strain)/0.70 .

Natick Data

The hand fitting method requires the data analyzer to construct an "average" curve for each set of test data obtained. The interpretive process thus occurs for every stress-strain curve and the quality of the data obtained depends to a large degree on the skill and experience of the analyzer. When the stress-time records are relatively free of oscillations, the averaged curve is not particularly difficult to fit. When there are extreme oscillations on the records, however, the averaging process becomes very subjective, and the analyzer has little confidence that his results will be repeatable. For this reason, the reduction of the Natick Lab data by hand fitting methods proved to be a relatively

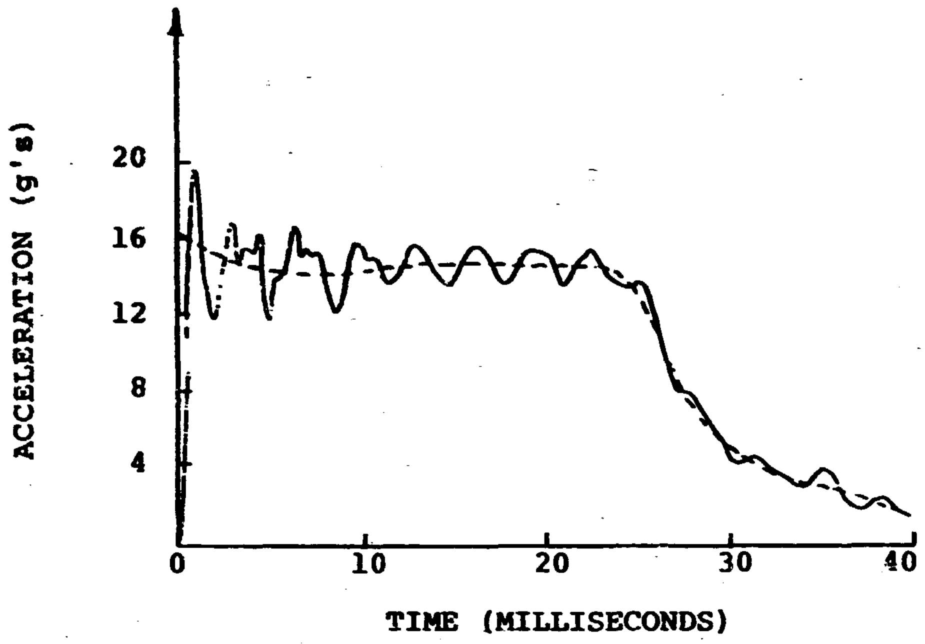


Fig. 1 Smoothing Process

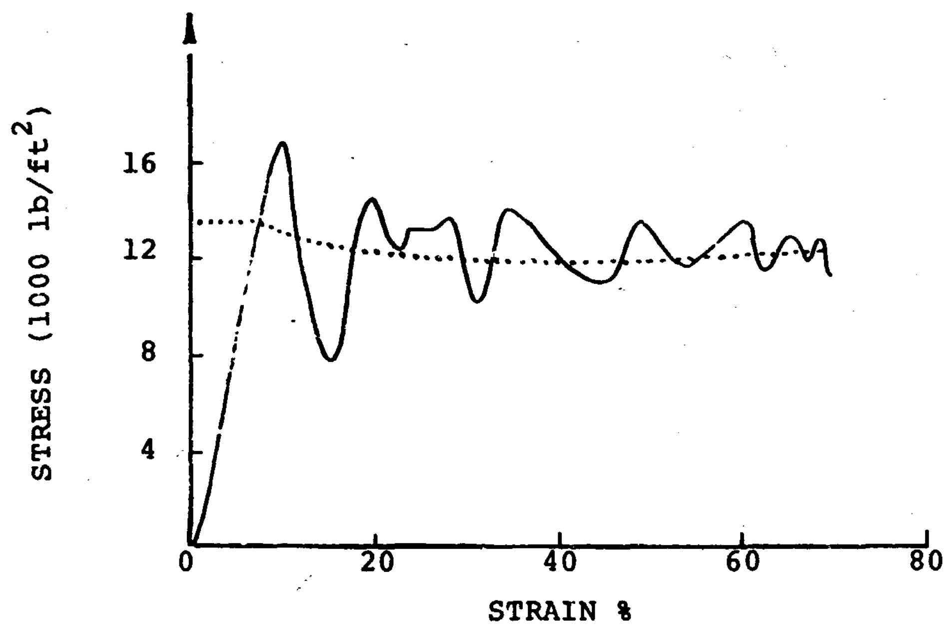


Fig. 2 Graphical Stress-Strain Curve

difficult problem. The difference in the appearance of the data obtained by EMRL for Honeycomb X sample 7 and that obtained by Natick for the same sample is evident from Fig. 3.* Two views of one of the Natick acceleration-time curves are shown in Fig. 4. The dotted line on both curve 1 and curve 2 represents the hand fitted average curve drawn by the analyzer on two different occasions, on two separate copies of the enlarged stress-time plot. Figure 5 shows how these two "average" curves compare. While the difference between the results obtained from the two averaged curves is not large, it is at least as large as the variance expected in the properties of the honeycomb.

Consequently, to try and improve the repeatability of the results of the data reduction, a mathematical least squares curve fitting procedure was developed using a digital computer. The decisions with respect to the interpretation of the properties of the honeycomb from the raw acceleration-time and displacement-time data still had to be made for this procedure, but these decisions could be incorporated into the selection of data points used in the computation and in the order of the polynomial used for the curve fitting. So once the computational method is established, the data analyzer only has to select specified points from the original data and no intermediate interpretive decisions are required on his part.

Least Squares Method

One method of analytically "fitting" a curve to a set of scattered data points is the method of Least Squares. Using this method, the coefficients of a polynomial of specified order are adjusted in such a way that the curve generated by this polynomial represents a "best fit" approximation to the actual data points. Referring to Fig. 6, the smooth curve shown is generated by a polynomial of order n and is represented by the equation:

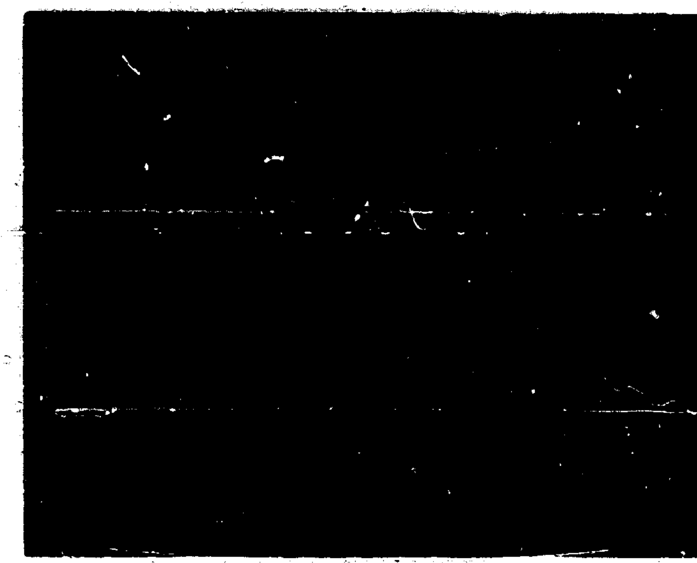
$$Y_P = A_0 + A_1X + A_2X^2 + A_3X^3 + \ldots + A_NX^N$$

where Y_P is the value obtained from the equation

---

*As indicated in the Data Interpretation section, this difference is probably due to the differences in testing techniques of the two facilities, including types and frequency response of accelerometers used, frequency response of electronic filtering used, and the mechanical systems used to accomplish the tests.

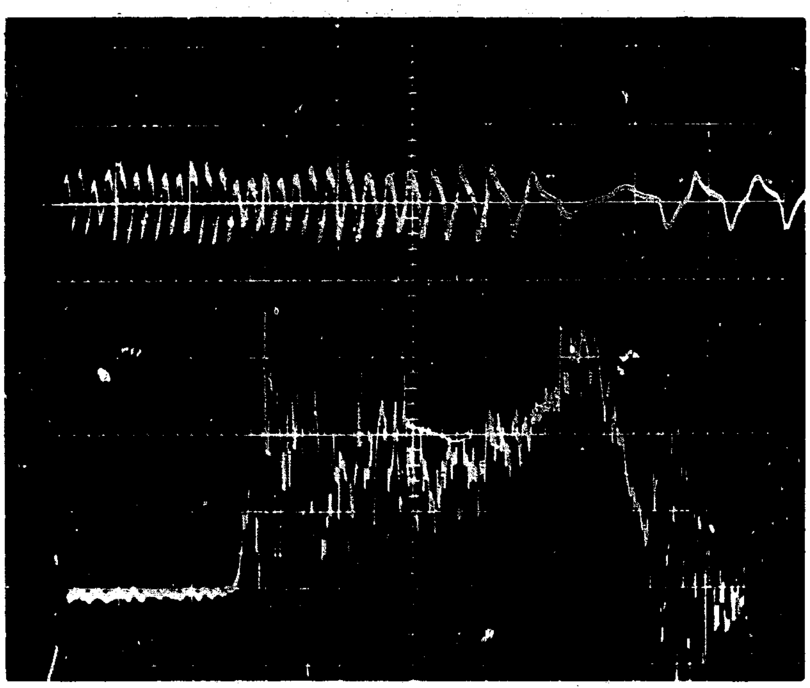
stress (psf)



time (milliseconds)

EMRL Honeycomb X-7 -- Acceleration Record

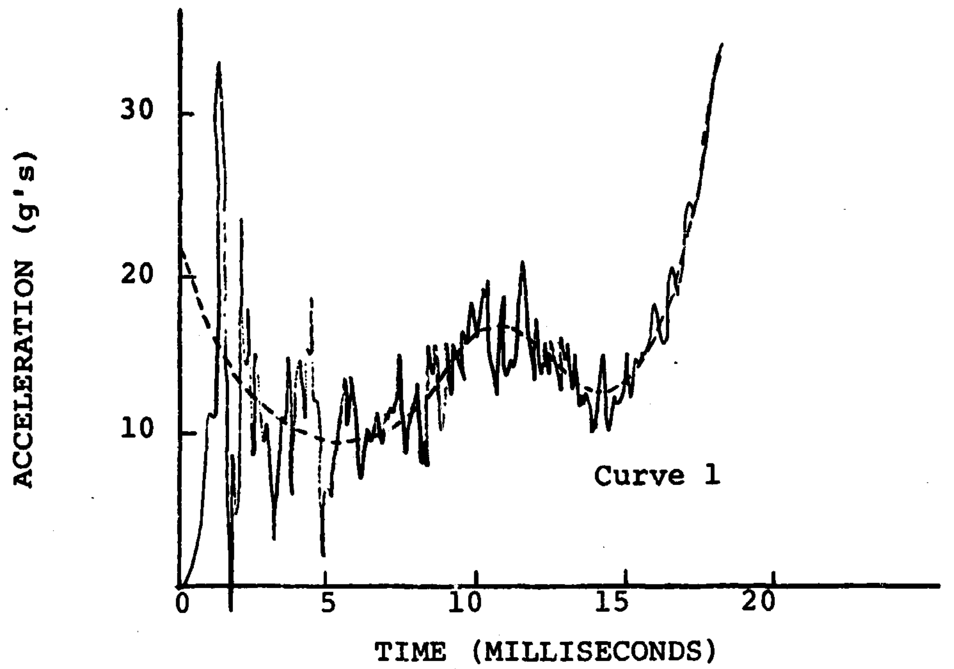
stress (psf)



time (milliseconds)

Natick Lab Honeycomb X-7 -- Acceleration Record

Fig. 3 Typical Acceleration Records



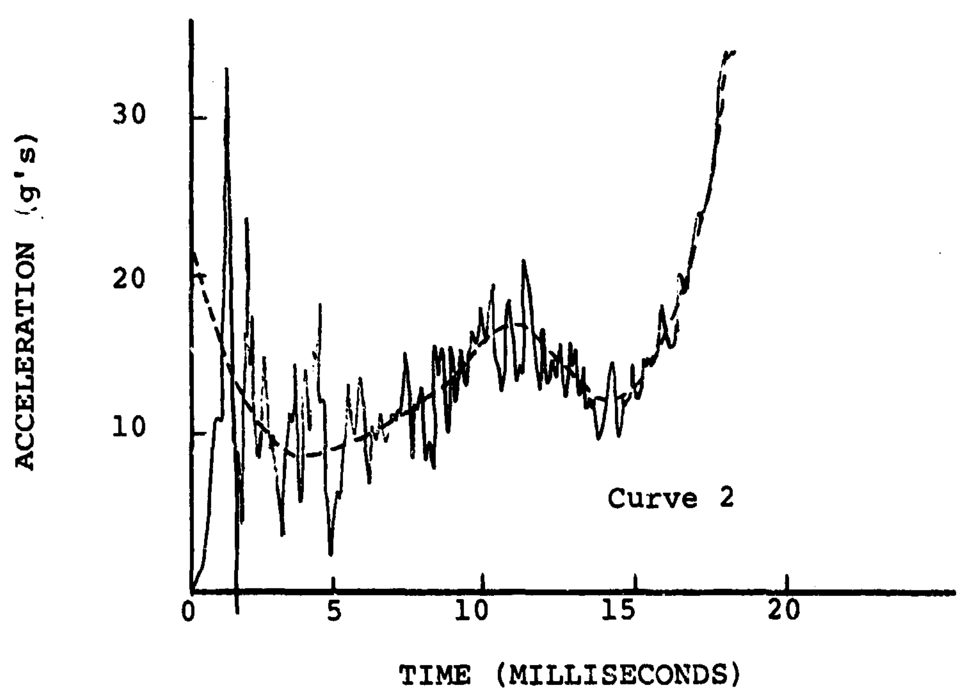


Fig. 4 Graphical Method on Natick Results

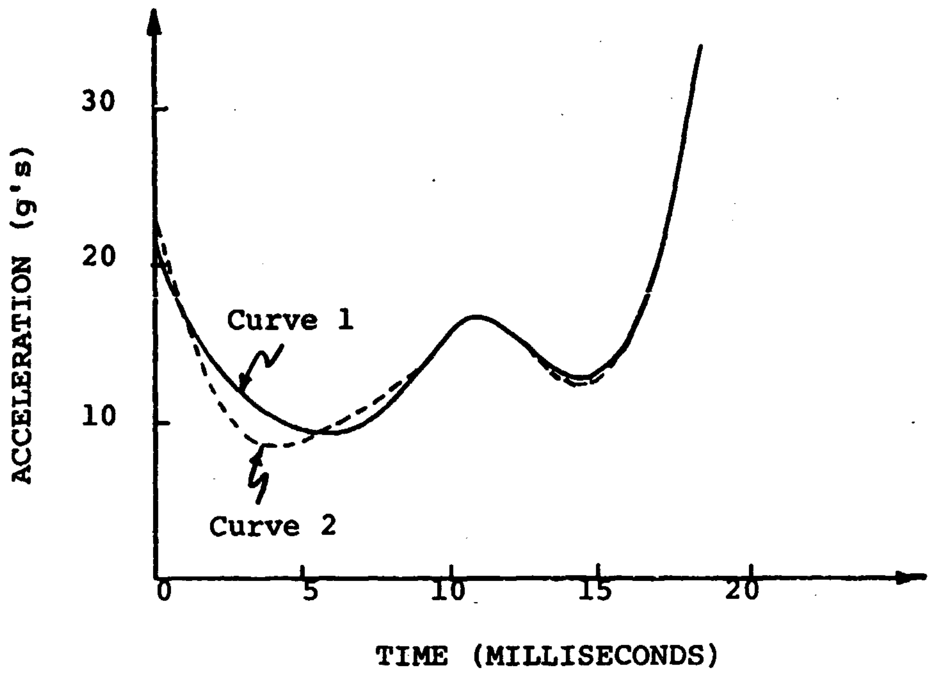


Fig. 5 Inconsistency in the Graphical Method

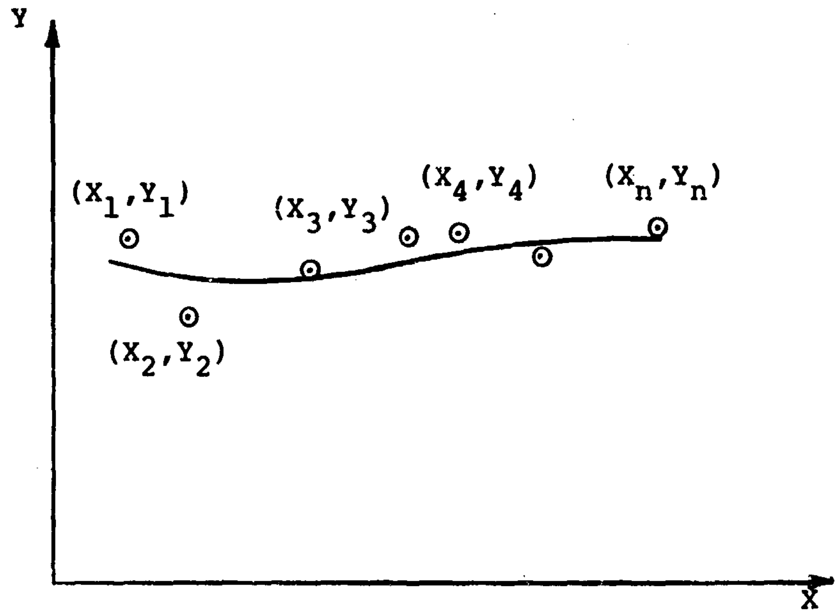


Fig. 6 Least Squares Curve Fitting

for the actual abscissa values, X.

The mean square difference between an actual data point, Y_i and the predicted "best fit" data point is:

$$\epsilon_{ms_i} = (Y_i - Y_{P_i})^2$$

To obtain the values of the coefficients for the polynomial given above, the sum of all the mean square differences between actual data points and predicted data points is minimized by differentiating this sum with respect to each coefficient, specifying that this derivative be zero for each equation obtained, and solving these equations simultaneously.

$$\frac{\partial}{\partial A_i}\left[\sum_{i=0}^{N} \epsilon_{ms_i}\right] = 0$$

The resulting equations are called "recurrence" equations and take the following form for a 2nd order polynomial

$$\sum Y_i = A_0 N + A_1 \sum_{i=1}^{N} X_i + A_2 \sum_{i=1}^{N} X_i^2$$

$$\sum_{i=1}^{N} X_i Y_i = A_0 \sum X_i + A_1 \sum X_i^2 + A_2 \sum X_i^3$$

$$\sum_{i=1}^{N} X_i^2 Y_i = A_0 \sum X_i^2 + A_1 \sum X_i^3 + A_2 \sum X_i^4$$

A computer program identified as LSCFWOP (Least Squares Curve Fitting with Orthogonal Polynomials), is available for solving these equations for large numbers of data points, and for high order polynomials.

Three choices had to be made with respect to the use of this data reduction method before it was applied generally to the honeycomb test records:

1. A method for selecting, from the original data, the data points that were to be used in the calculations was chosen.

2. Based on the guidelines established for the best "average curve" in the Data Interpretation section, the order of the polynomial chosen to fit the data was selected.

3. A method for accounting for the apparent lag in the initial stress rise was selected.

The method for selecting the data points to be used in the calculations was based on two guidelines. First, a sufficient number of significant points should be used to adequately represent the original curve. Second, these significant points should be easily recognizable to a relatively unskilled data analyzer. The points chosen to satisfy these conditions were the peak points of all maximum and minimum oscillations of the original curve and all points of inflection occurring between these peaks.

The general shape of the "average" curve was determined by the order polynomial used to generate this curve. To the eye of the data analyzer, the general shape of the original stress-time records appears to have up to five changes in inflection, or bends. A sixth order polynomial is required to generate a curve with this many inflections. Consequently, the order of the polynomial that generates the best fit curve probably lies somewhere between 2 and 6. A trial run for a specific honeycomb test record was made to determine the coefficients of polynomials of order 2 through 6 to see which provided the apparent "best fit." Figure 7 shows the original data used and the curves generated by 2nd, 4th, and 6th order polynomials.

The curves, generated from points selected in the manner described above, were compared to the original data on the basis of the apparent best fit, and conformation to general shape.

The 6th order curve was the apparent best fit, except for the region of the curve between zero strain and the

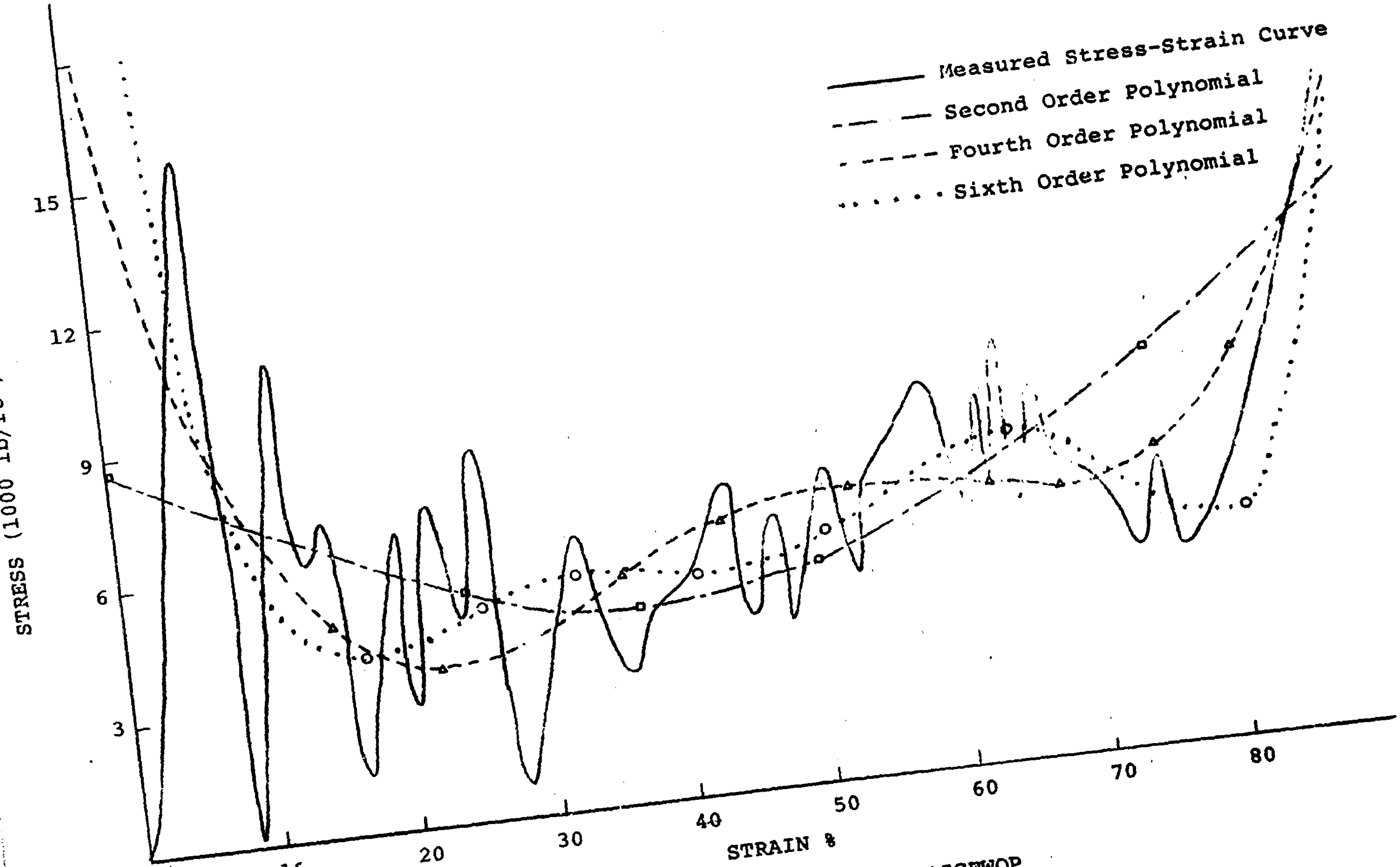


Fig. 7 Fitting Curves Using LSCFWOP

delayed, indicated yield strain. To compensate for the high indicated stresses in this region, the initial yield point was shifted back to the zero strain level and the programs were rerun. The effect of this shift is indicated by Fig. 8. The general shape of the best fit curve looked reasonable and comparisons of the areas beneath this best fit curve, a hand fitted curve, and the actual point by point correlation curve, indicated satisfactory agreement.

Integration of the polynomial generated curve to obtain the area beneath it from zero to 70% strain was performed by a digital computer. From this integration, values for the energy absorbed to 70% strain and the average crushing stress to 70% strain were easily determined.

A comparison between crushing stress values obtained by the hand fitting method and those obtained by the least squares-computer method is made for the entire series of tests conducted by EMRL and is included in the next section of this report. After this comparison was made, the least squares computer method was used to reduce the Natick tests and the results represent EMRL's evaluation of the Natick Data.

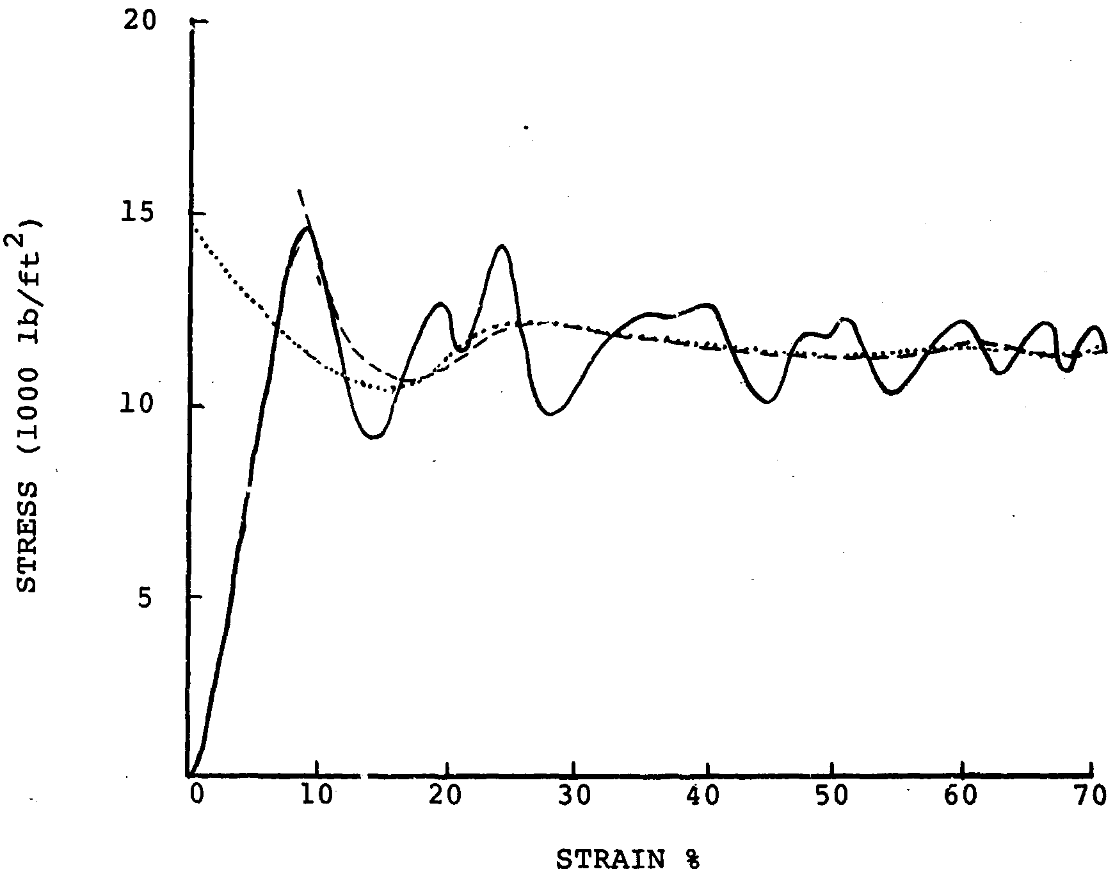


Fig. 8 Shift of Initial Peak Stress

COMPARISON OF RESULTS

Tables

Tables 1 and 2 contain sample by sample listings of the average crushing stresses determined for the honeycomb specimens tested. Table 1 presents the results for the Honeycomb X samples and Table 2 presents the results for the Honeycomb Y samples. For each honeycomb sample listed, crushing stress values are shown for the EMRL hand fitted data, the EMRL data reduced by computer (LSC), the Natick reduced Natick data, and the Natick data reduced by EMRL computer. The mean or average value of each set of samples tested is included at the bottom of each listing, along with the standard deviation for the set. The average energy dissipation to 70% strain is also listed.

Methods for Comparison

Since the intent of the test plan was to compare the average crushing stresses for honeycomb specimens cut from the same honeycomb panels, the results of the tests are first compared on a sample by sample basis. Some indication of the sample by sample correlation can be had simply by noting the general trends of the results listed in the tables. However, a more formal method for determining the degree of correlation between two sets of results is to obtain a best fit straight line relationship, or first order regression line, between these sets using the corresponding sample values to determine the points of a scatter diagram. This diagram is an x-y plot with the first "random variable" plotted as the ordinate and the second plotted as the abscissa. After the regression line is determined, a measure of the spread of the actual data points about this best fit approximation is provided by the correlation coefficient. A sample scatter diagram illustrating the comparison between the EMRL hand reduced data and the EMRL computer reduced data is provided as Fig. 9. Using the following definitions

S = Average crushing stress to 70% strain for a given honeycomb specimen

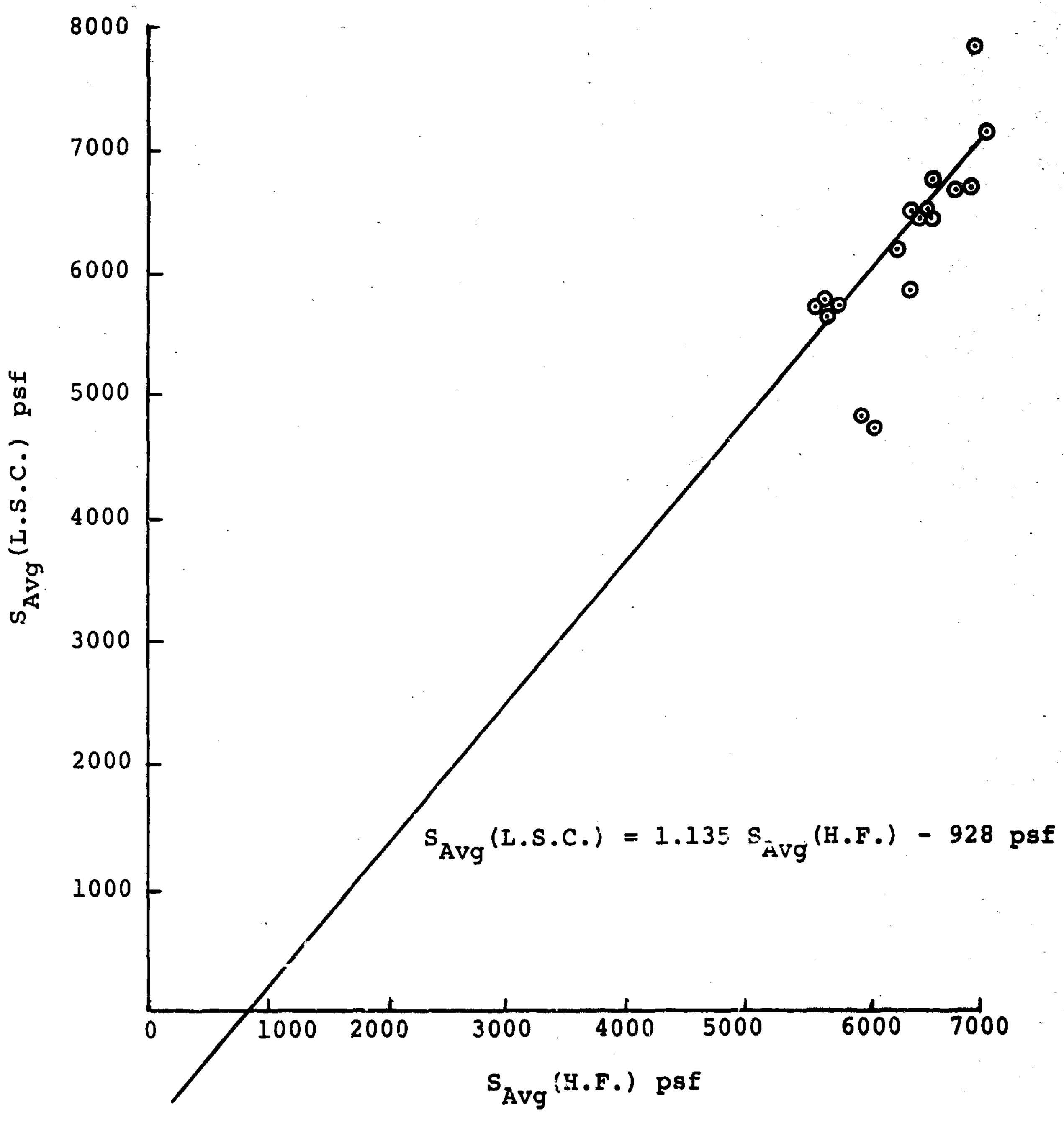


Fig. 9 Regression Line for EMRL Honeycomb X

TABLE 1

TEST RESULTS FOR HONEYCOMB X

	Engineering Mechanics Research Laboratory		Natick Laboratory	
Sample	Aver. Stress Hand Fitted psf	Aver. Stress Computer psf	Aver. Stress (Natick Computed) psf	Aver. Stress Computer psf
1A	6140	4757	6125	5970
2A	-	-	6070	6672
3A	7050	7828	5910	6305
3B	7120	7149	-	-
4A	5620	5723	6910	7521
4B	5750	5763	-	-
5A	6040	5879	5625	5745
5B	6540	6446	-	-
6A	5730	5719	6075	5886
6B	5850	5756	-	-
7A	6340	6470	6930	7743
7B	6990	6670	-	-
8A	6410	5846	6330	7125
8B	6360	6198	-	-
9A	6680	6721	6380	6337
9B	6580	6471	-	-
10A	6620	6430	5870	6019
10B	6890	6696	-	-
Mean Value	6272	6335	6223	6530
Standard Deviation	467	670	405	674
Aver. Energy Dissipated	4390	4420	4360	4560

TABLE 2

TEST RESULTS FOR HONEYCOMB Y

Engineering Mechanics Research Laboratory			Natick Laboratory	
Sample	Aver. Stress Hand Fitted psf	Aver. Stress Computer psf	Aver. Stress (Natick Computed) psf	Aver. Stress Computer psf
1A	11070	10849	10900	12278
1B	11771	11076	-	-
2A	11291	11360	11400	9490
2B	11490	11153	-	-
3A	11220	10336	10650	12080
3B	11750	10373	-	-
4A	10900	10340	11200	13069
4B	10570	9996	-	-
5A	11700	12050	11450	12343
5B	12180	11536	-	-
6A	11061	10885	11510	12561
6B	11600	10692	-	-
Mean Value	11383	10887	11185	11970
Standard Deviation	429	563	313	1150
Aver. Energy Dissipated	7960	7610	7810	7870

$$M = \frac{1}{N} \sum_{i=1}^{N} S_i$$

$$\sigma = \left[\frac{1}{N} \sum_{i=1}^{N} (S_i - M)^2 \right]^{\frac{1}{2}}$$

$$\mu_{AB} = \frac{1}{N} \sum_{i=1}^{N} (S_{A_i} - M_A)(S_{B_i} - M_B)$$

A and B subscripts refer to the two different sets of data, or random variables, used in the comparisons.

The equation for the regression line is:

$$S_{A_P} = M_A + \frac{\mu_{AB}}{\sigma_B^{\,2}} (S_B - M_B)$$

where S_{A_P} is the predicted crushing stress for the A samples.

The correlation coefficient ρ, defined as

$$\rho = \frac{\mu_{AB}}{\sigma_A \sigma_B}$$

is a measure of the spread of the points of the scatter diagram about the regression line, and may vary from minus one to plus one in magnitude.

Ideally, the regression lines for the sets of data compared in this report would all pass through the zero point and have slopes of 45°, and the correlation coefficients would all be 1.0. This would mean that each sample tested had the exact same crushing stress as its counterpart selected from the same honeycomb panel. The closer a given set of results comes to meeting these conditions, the closer the quantities defined above will be to the ideal. If the results are totally unrelated, the value of the correlation coefficient will be 0 and the slope of the regression line may be anything from plus to minus infinity.

For further reference to these statistical procedures, Introduction to Probability and Statistics, by Birnbaum, or any number of similar texts on statistics, may be consulted.[4,5]

While the statistical methods of correlation provide a formal procedure for obtaining some insight into the relationship between "random variables," placing too much emphasis on the actual numbers obtained for the correlation coefficient and the slope of the regression line could be very misleading. These quantities are best used as general comparison indicators and are only defendable as such. Needless to say, the smaller the statistical sample used to provide these indicators, the less the confidence that can be placed in the results.

A more general indication of the correlation between two sets of data is obtained simply by comparing the average values of these sets. These average value indicators are the means, and the standard deviations, and they can provide a useful first glance correlation. Even though the sets of data may appear essentially independent on a sample by sample basis, they may very easily have the same statistical average values, indicating that they may derive from the same "sample space" (in this case, the entire collection of honeycomb panels from which the samples were taken).

Both the sample by sample and the average value correlation techniques are used to provide some insight into the relationship between the sets of data selected for comparison in the next section of the report.

EMRL Data Reduction Comparisons

In order to establish a measure of the agreement between the hand fitting method of data reduction and the least squares computer method of data reduction, the results obtained by both methods, for both the Honeycomb X and the Honeycomb Y tests, were compared sample by sample and on an average value basis. Since these results were actually for the same tests, and not for just similar tests, anything less than perfect correlation is due to differences in the data reduction techniques and represents what can be considered to be errors in one or the other technique. As can be seen from Table 1, the trends, sample by sample, of the results appear to be generally similar. This is borne out by the slope of the regression line and the value of the correlation coefficient. The equation of the regression line for the Honeycomb X data is

$$S_{Avg.}\text{ (Least Sq. Comp.)} = 1.135\ S_{Avg.}\text{ (Hand Fitted)} - 928\text{ psf.}$$

And the value of the correlation coefficient for these two sets of data is:

$$\rho = 0.784 \quad .$$

The equation for the regression line for the Honeycomb Y data is:

$$S_{Avg}(L.S.C.) = 2.1\ S_{Avg}\ (H.F.) - 13,100 \text{ psf} \quad .$$

And the value of the correlation coefficient is

$$\rho = 0.608 \quad .$$

On an average value basis, the means for the sample results are

	Honeycomb X	Honeycomb Y
Hand Fitted	m = 6335	11,383
Least Squares Computer	m = 6272	10,887

From these values, the mean values for the Honeycomb X data are within 1% of one another, while those of the Honeycomb Y data are within 5% of one another.

Considering the number of samples involved, these sets of results correlate reasonably well. The correlation for the Honeycomb X data is better, probably because the raw data were relatively free of extreme oscillations* in the stress-time records and were easier to interpret. As a general rule throughout these comparisons, the more extreme the oscillations in the stress records, the worse the statistical correlation was for the sets of results.

Natick Data

A similar correlation of the Natick computations with the LSC results for the Natick data produced the following:

The regression line equation for the Honeycomb X data:

$$S_{Avg}(Natick) = 0.533\ S_{Avg}(L.S.C.) + 2743 \text{ psf}$$

*This is believed to be due in part to the lower acceleration level and in part to the slight precrushing of Honeycomb X in the manufacturing process.

and the correlation coefficient

$$\rho = 0.888 \ .$$

The regression line equation for the Honeycomb Y data:

$$S_{Avg}(\text{Natick}) = 11{,}750 - 0.047\ S_{Avg}(\text{L.S.C.})$$

with the correlation coefficient

$$\rho = 0.174 \ .$$

Record Number 2 in the Honeycomb Y results, because of the violent oscillations on it was particularly difficult to hand fit. Probably because of this the average stresses indicated by the two methods of reduction differ by almost 2000 psf. A record of this type probably should be discarded if it turns up in a testing program. If it is discarded here, the regression line equation becomes

$$S_{Avg}(\text{Natick}) = 5342 \text{ psf} + 0.465\ S_{Avg}(\text{L.S.C.})$$

and the correlation coefficient becomes:

$$\rho = 0.48 \ .$$

The means for the Honeycomb Y results, reduced by the two methods become:

Natick reduction	11,142 psf
Least Squares Computed	12,466 psf .

These values are now within 10.6% of each other. This is probably an intolerable difference but it should be noted that only 5 tests are represented in these calculations. This is too small a number to give a reliable comparison of the two methods of data reduction.

For the Honeycomb X samples reduced by the two methods, the means are

Natick reduction	6223 psf
Least Squares Computed	6530 psf .

These values agree within 5% of each other. The better agreement is due in part to the reduction in oscillation on the records, as compared to the Honeycomb Y records, and to the greater number of samples.

Honeycomb Crushing Stress Comparisons

The results to be compared now are those obtained from tests which were actually different, though planned to be as closely alike as possible through use of honeycomb specimens cut from the same panels. The regression line equations and correlation coefficients obtained from the computer analyzed data are as follows:

Honeycomb X

Regression Line Equation $S_{Avg}(EMRL) = 6083 + 0.029\ S_{Avg}(Natick)$

Correlation Coefficient $\rho = 0.029$

	EMRL	Natick
Mean Values	6272	6530
Standard Deviation	670	674

Honeycomb Y

Regression Line Equation $S_{Avg}(EMRL) = 11{,}840 - 0.08\ S_{Avg}(Natick)$

Correlation Coefficient $\rho = -0.1640$

	EMRL	Natick
Mean Values	10,887	11,970
Standard Deviation	563	1150

The mean values for these results compare within 4.2% for the Honeycomb X tests and within 10% for the Honeycomb Y. The regression line equations and correlation coefficients obtained from the hand fitted analysis of the data are:

Honeycomb X

Regression Line Equation $S_{Avg}(EMRL) = 10{,}054 - 0.586\ S_{Avg}(Natick)$

Correlation Coefficient $\rho = -\ 0.51$

	EMRL	Natick
Mean Values	6272	6223
Standard Deviations	429	563

The mean values for these results compare within 1% for the Honeycomb X tests and within 4.2% for the Honeycomb Y tests.

Sample by Sample Comparison

For eight of the tests conducted by EMRL on Honeycomb X, results were obtained for both the A and the B specimens which had been cut from the same honeycomb panel. A correlation between the computed sample A results and the computed sample B results, where all tests were conducted by the same facility and under the same conditions, provides some indication of the uniformity of the properties that should be expected for the honeycomb panel. The results of this correlation are as follows:

Regression Line Equation S_{Avg}(A samples) = 1.21 S_{Avg} (B samples) - 1623 psf

Correlation Coefficient $\rho = 0.83$

The sample by sample correlation between the EMRL results and the Natick results does not indicate this degree of comparison. However, the EMRL-Natick correlation is biased by the effects of the different testing techniques of the two facilities. It seems reasonable to expect the crushing stress values of specimens selected from the same honeycomb panel to agree more closely than those from specimens selected at random from the entire shipment.

Average Value Comparison

On an average value basis, the results of the test series compare reasonably well for both methods of data reduction and for the tests of both facilities. As indicated in Tables 1 and 2, the standard deviations for the sample results reduced by computer are consistently larger than those for the results reduced by hand fitting. The probable reason for this is the data analyzer's built in bias toward uniformity in his results caused by his awareness of the results he has already obtained.

Statistical Inference

The underlying reason for conducting honeycomb tests on a sampling basis such as those reported is to provide some method for predicting the properties of entire honeycomb shipments. From the results of these sample tests, it should be possible to statistically infer something concerning the properties of the entire shipment. For instance, from the test values provided by the sample, the mean value of the crushing stress of the entire shipment may be predicted within certain specified limits with a given probability or given degree of confidence. If the crushing stress variable can be assumed to have a normal or nearly normal probability distribution, these limits can be specified with relatively good confidence, depending upon the number of sample tests made. For a normally distributed crushing stress variable with a given mean and standard deviation, Student's[4] theorem provides the following prediction for the overall mean value with the corresponding limits:

$$M \pm t_c \frac{\sigma}{\sqrt{N-1}}$$

where t_c is called the critical value or confidence coefficient and is read directly from a tabulation of Student's t Distribution.

For the EMRL Honeycomb X test series consisting of 17 samples, the probability that the crushing stress mean value of the entire honeycomb shipment will lie between the range of

$$(6272 - 252)\text{psf} \leq M \leq (6272 + 252)\text{psf}$$

will be P = 0.95. The range ±252 psf in this case was determined by the choice of 0.95 as the probability, or confidence interval. For narrower limits, the probability necessarily is reduced. Similar predictions can be made for the standard deviation of the entire shipment using the Chi Square Theorem.[4]

CONCLUSIONS

1. The results of the honeycomb tests are dependent on the method of data reduction used, particularly where large oscillations appear on the stress-time records and the data analyzer is called upon to make subjective interpretations. The computerized Least Squares data reduction method is less arbitrary than the Hand Fitting method and the results obtained from this method are more defendable, from a repeatability standpoint, for this reason. Where a honeycomb contractor's incentives are related to the results of these sample tests, the fairest tests are the most objective tests. Consequently, the least squares method is preferable to the graphical method, even though there is greater scatter in the results obtained with this method.

2. The results of the independent, parallel test programs conducted by EMRL and Natick Labs are not consistent on a sample by sample basis. On a statistical average value basis, however, the results are reasonably consistent. Differences in the statistical averages can be attributed to a number of causes, including not only differences in test techniques and data reduction methods, but also the relatively small statistical sampling involved.

LIST OF REFERENCES

1. Chalupnik, J. D., A Streak Camera for General Laboratory Use, SMRL RM 9, Engineering Mechanics Research Laboratory, The University of Texas, Nov. 1964.

2. Maschi, Angelo P., Energy Dissipation Characteristics of Hand Expanded Paper Honeycomb, Project No. 1K141812D183, U. S. Army Natick Laboratories, Natick, Massachusetts, Feb. 1964.

3. Dynamic Stress-strain Curve Generator for Cushioning Materials, Engineering Mechanics Research Laboratory, The University of Texas, EMRL-RM-1025, March 31, 1967.

4. Birnbaum, Z. W., Introduction to Probability and Mathematical Statistics, Harper and Brothers, 1962.

5. Parzen, E. P., Modern Probability Theory and Its Applications, John Wiley and Sons, Inc., 1960.

APPENDIX I

DESCRIPTION OF ENGINEERING MECHANICS RESEARCH LABORATORY DROP TEST FACILITIES

APPENDIX I

Test Facilities

The guided free-fall drop tower used by the Engineering Mechanics Research Laboratory to perform the tests reported in the body of this report has the following specifications:

	Lower Limit	Upper Limit
Drop height	0 ft	85 ft
Impact velocity	0 fps	74 fps
Weight of mass	248.5 lbs	2500 lbs
Specimen area	0 ft^2	2 ft x 2 ft square
Specimen height	0 ft	limited by stability of stack during impact

Photographs of various features of this facility are shown in Figs. I-1, I-2, I-3. The primary mass is made up of wide flange beams welded together to form a box with diagonal bracing, with three-eighths inch aluminum plates bolted to the beams so as to form the top and bottom of the box. This mass may be increased by bolting steel plates to the bottom of it.

The base or anvil on which the specimen is placed to be impacted by the falling mass is a 2' - 10" x 3' - 5" x 1' - 10" reinforced concrete block resting on top of a 14 ' x 16 ' reinforced concrete slab 18" thick. A one-half inch thick steel plate is bolted and grouted to the top of the concrete block to provide a tough, hard impact surface.

The force exerted by the mass on the cushioning material during crushing is derived from the acceleration of the impacting mass. This acceleration is measured with a fluid damped accelerometer and recorded as a function of time with a Polaroid camera and an oscilloscope. The instantaneous height of the cushioning material during impact is recorded photographically with a Streak Camera specially built for this application. Peak crushing stress, average crushing stress, and energy absorption are deduced from the measured values of instantaneous stress and strain. Details of the test procedure and of the preparation of stress-strain curves follow.

Fig. I-1 Overall View of 85 ft Drop Facility

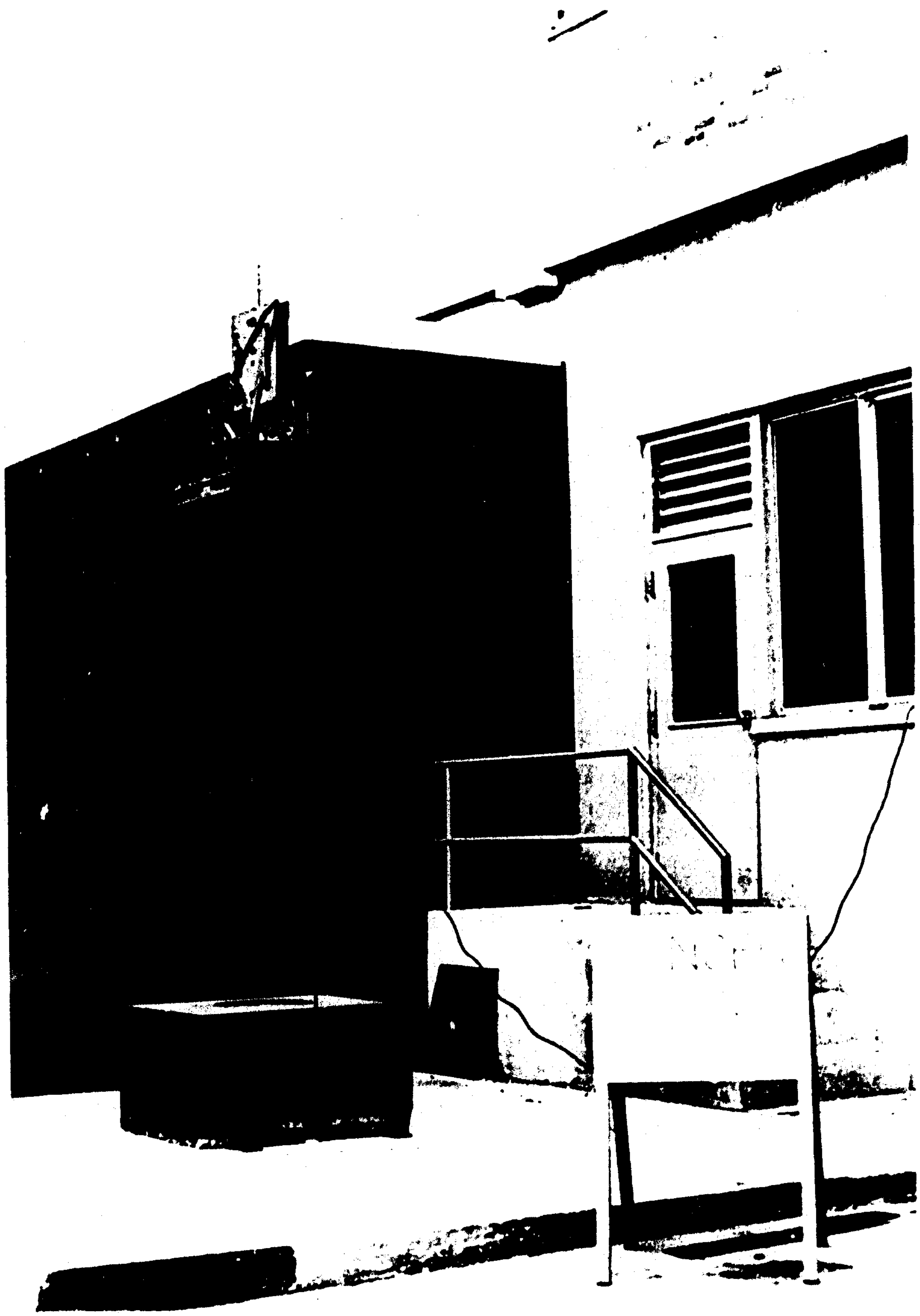


Fig. I-2 Mass and the Concrete Anvil

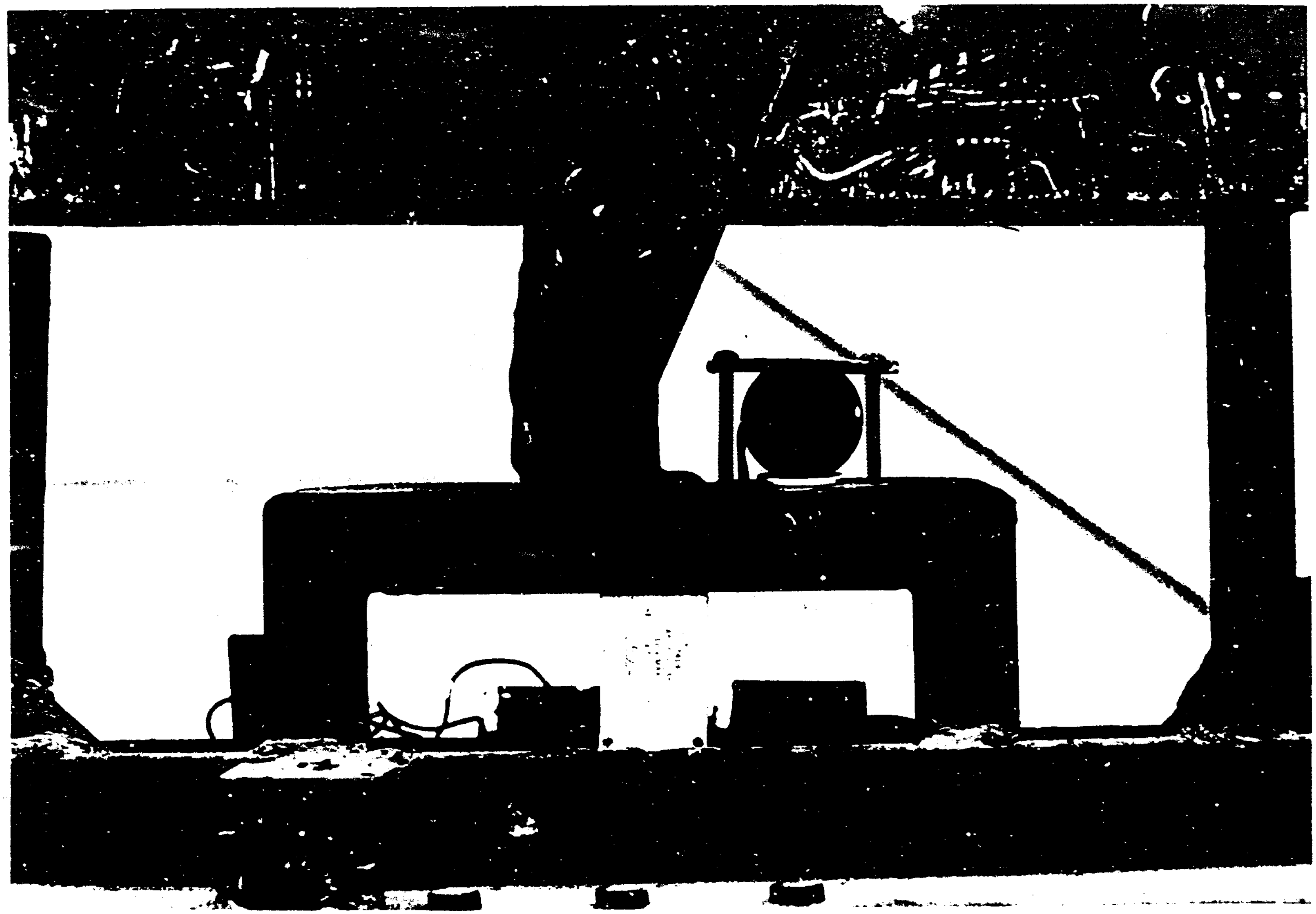


Fig. I-3 Close-up of the Accelerometer and Light Source

Stress Measurements

The crushing stress is obtained by dividing the crushing force by the area of the specimen. The crushing force exerted by the mass on the specimen, is calculated using Newton's second law of motion with the measured acceleration and the impacting mass. Acceleration is measured with an accelerometer which is mounted at the center of the top face of the mass. A 500g, fluid damped Statham accelerometer with a natural frequency of about 2000 cps is used. This accelerometer is the unbonded resistance type with an internal circuit in the form of a bridge. The output voltage of the bridge multiplied by a manufacturer supplied calibration constant represents the instantaneous acceleration of the mass. This output voltage is recorded with respect to time using a high gain Tektronix oscilloscope equipped with a Polaroid camera. A zero level trace and a calibration voltage are also recorded with the acceleration trace. The calibration signal is obtained by shunting one leg of the accelerometer bridge with a known precision resistance. The resulting output voltage is equivalent to the voltage output from the accelerometer for a steady level of acceleration. The zero level and calibration traces are recorded just prior to drop. The acceleration record is then superimposed on this picture. A typical acceleration record is shown in Fig. I-4.

Strain Measurements

The instantaneous strain* in the specimen during impact is obtained by dividing the instantaneous reduction in height of the specimen by its original height. A streak camera is used to record the instantaneous reduction in height. The film for the streak camera is mounted on a rigid vertical cylinder which is driven by a synchronous motor at 1800 rpm. A small, intense, prefocused lamp is mounted on the top of the mass and the lens of the streak camera focuses an image of this pinpoint of light on the surface of the rotating drum. As the mass moves vertically, the light also moves with respect to the drum. The vertical distance the light moves on the film is linearly related to the vertical distance the lamp and mass have moved during impact. The horizontal distance the light moves on the drum is directly

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*This is only an average strain since the crushing is never uniform in the direction of force application. Crushing usually starts at the top of the specimen and proceeds toward the bottom.

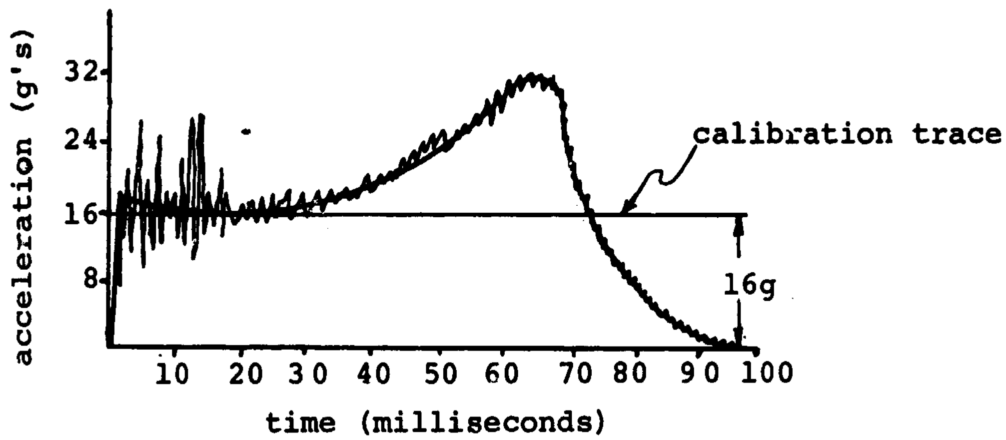


Fig. I-4 Acceleration Time Record

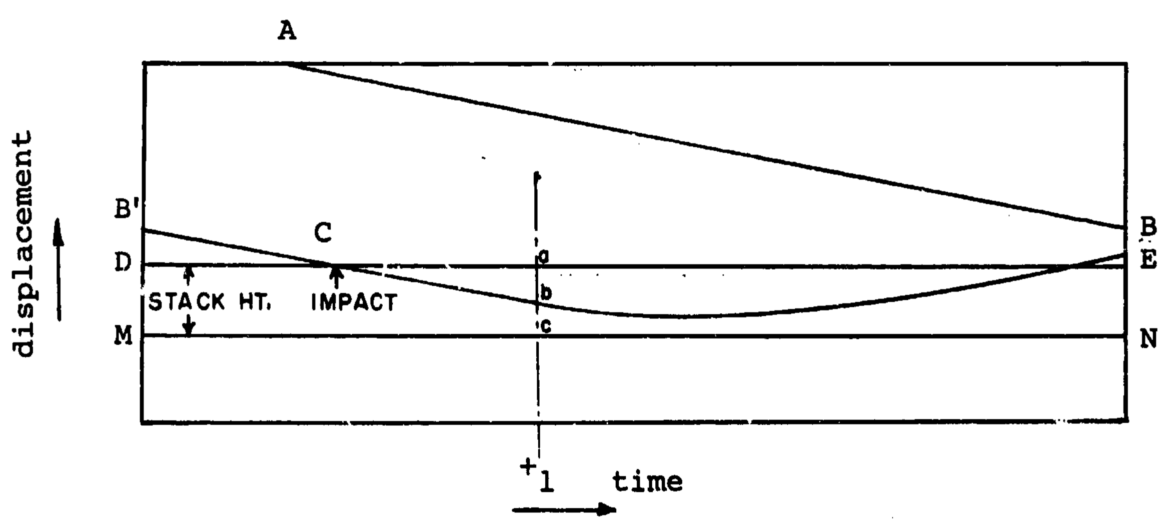


Fig. I-5 Typical Streak Record of Instantaneous Displacement related to time. Thus, the resulting streak on the film indicates the position of the mass with respect to time. A zero level streak is obtained by photographing the lamp while the mass rests directly on the impact block. An original height streak is obtained by photographing the lamp while the mass rests on the uncrushed specimen. A typical streak record is shown in Fig. I-5. The straight inclined line AB at the top of the record represents the motion of the mass as it comes into camera view before impact. This line continues at the left side of the record at B'. Impact occurs when this inclined line crosses the prerecorded original height streak DE at C. Thereafter, the streak is curved and the amount of crushing of the sample is proportional to the distance between the streak and the line DE. The proportionality factor is obtained from the distance between the original height streak DE and the zero level streak MN. As a matter of fact, the original height need not be known. The strain, as defined above, at a time t_1, is the ratio ab/ac.

The time scale may be found directly from the diameter and rotational speed of the drum. These streak records can be made in broad daylight if a dark background is provided.

Impact Velocity

Since the mass falls with essentially no external forces except gravity acting upon it up until the time of impact, the impact velocity may be calculated from the relation:

$$V = \sqrt{2gh}$$

The drop height is measured by an electronic counter that indicates the number of turns of a precisely dimensioned drum rotating in contact with the main lift cable. These measurements are easily repeatable within five per cent. This means that the impact velocity is repeatable within two and one-half per cent. At the lower drop heights and where greater precision is required, a direct measurement of height can be made with a tape.

The impact velocity is also obtainable from the slope of the line AB in the streak record shown in Fig. I-5.

Preparation of Stress-Strain Curves

The acceleration and streak records shown in Figs. I-4 and I-5 are enlarged and plotted to the same time scale using a telereader and an x-y plotter. The instant of impact is marked on both enlargements. Previous studies have indicated that the oscillations which appear on the stress record are caused primarily by vibrations excited in the mass by the impact and are therefore not of any particular significance so far as the stress-strain curve is concerned. Consequently, the stress curve is "hand smoothed" as shown in Fig. I-4. The stress records usually show a short delay between the time the impact force begins to develop and the time at which it reaches a peak. This delay is caused by the mass not making an instantaneous plane impact on the specimen, and by the time constant of the accelerometer. The former can not be avoided completely. It can only be minimized and then neglected in the construction of the stress-strain curves. Consequently, zero time for the force record is assumed to be the time at which an extrapolation of the initial steeply rising portion of the record cuts the time axis. This zero time as shown in Fig. I-4 corresponds to the impact time shown at C in Fig. I-5. The time constant of the accelerometer is also taken into account in reducing the data as will be explained later when the average crushing stress is discussed.

Stress is plotted as a function of strain by eliminating the parameter, time, from the stress-time and strain-time records. A typical curve prepared in this way is shown in Fig. I-6. The relatively constant crushing properties of honeycomb are restricted to approximately 70 per cent strain of the specimen, since "bottoming" begins at about that strain level. When "bottoming begins," the stress level rises sharply because the relatively open structure of the honeycomb has been changed to an almost solid structure and very little more crushing can occur. The energy dissipation properties of the honeycomb are measured with respect to 70 per cent strain therefore, and are obtained from the dynamic stress-strain curve by measuring the area underneath this curve between the 0 and 70 per cent strain levels and multiplying by a scale factor. The area in the small triangular area between the stress axis and the stress-strain curve is included because it is assumed that peak stress is reached virtually instantaneously on the time scale of the stress records. If this assumption were not made, one would have to conclude that a linear elastic strain of nearly two per cent is developed. As a matter of fact, the linear strain is too small to measure by the method used here. The apparent linear strain is produced by the accelerometer rise time which is approximately one-eighth millisecond. During that time, a strain of 1 to 1.5 per cent is developed when the impact velocity is 29 fps and the stack height is three inches.

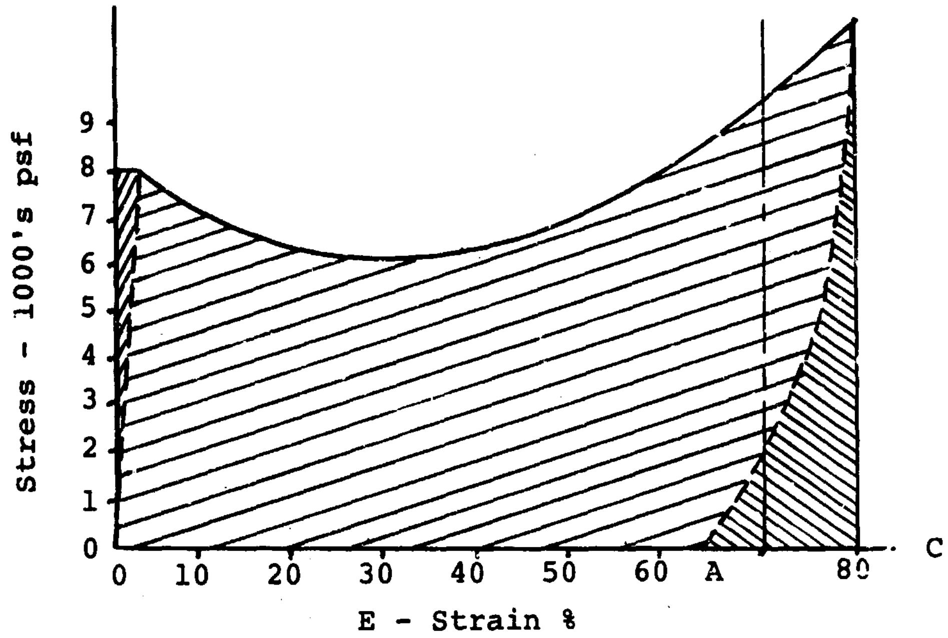


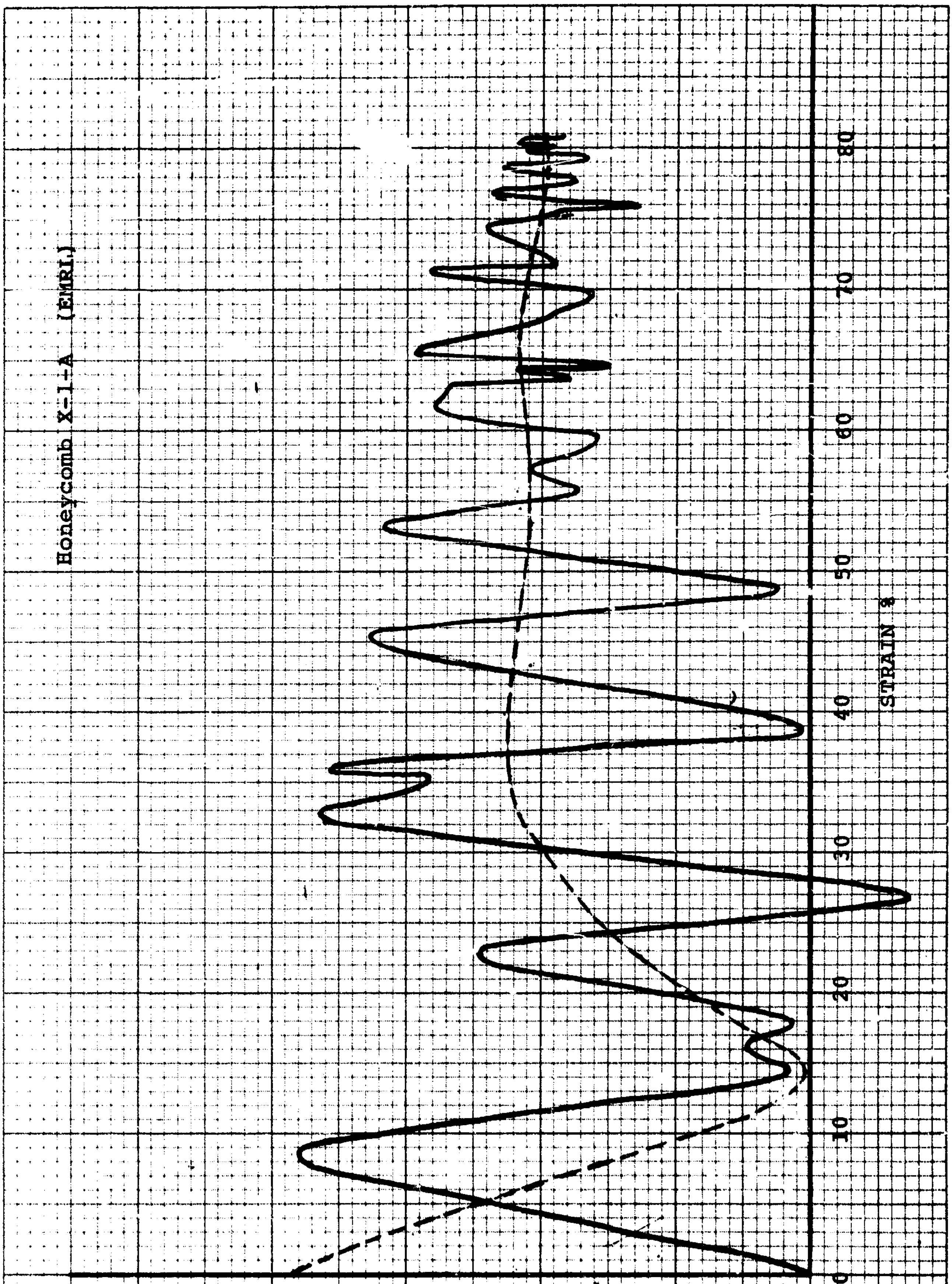
Fig. I-6 Hypothetical Stress-Strain Diagram for Paper Honeycomb

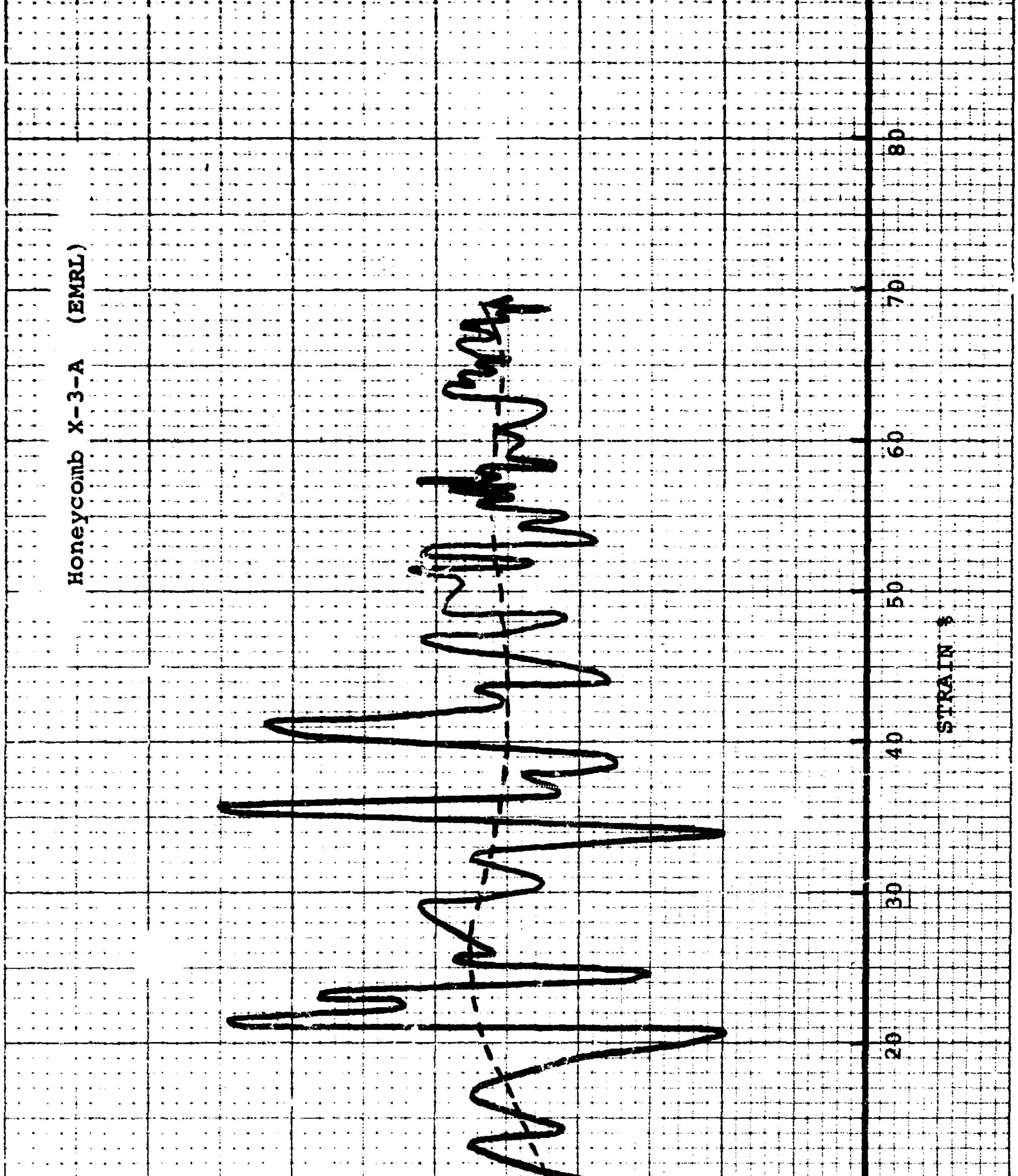
The area ABC shown in Fig. I-6 represents the rebound energy, or the elastic energy stored in the specimen.

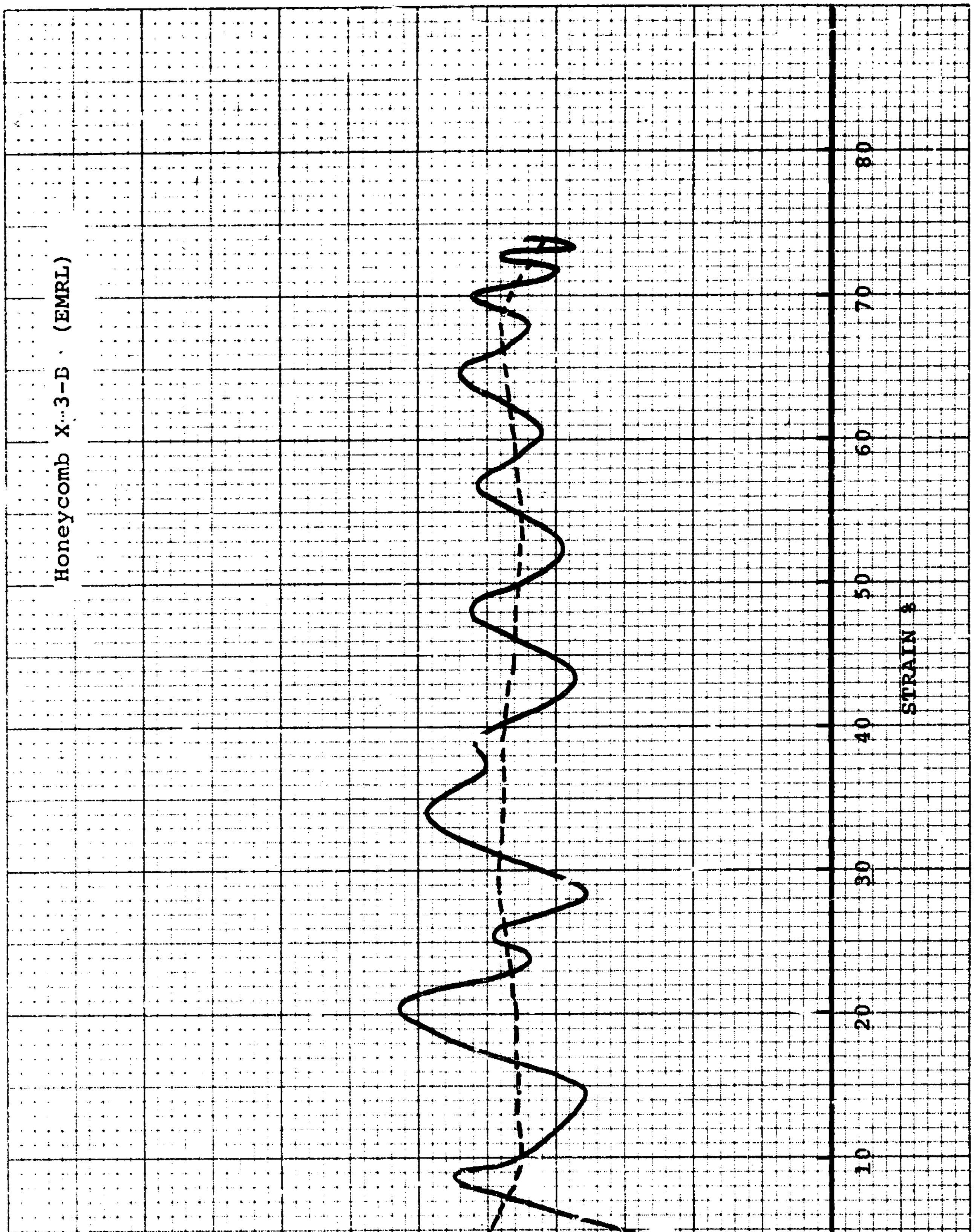
The average dynamic crushing stress obtained by dividing the energy dissipation value by 0.7 represents the mean value of stress over the 0 to 70 per cent range of strain.

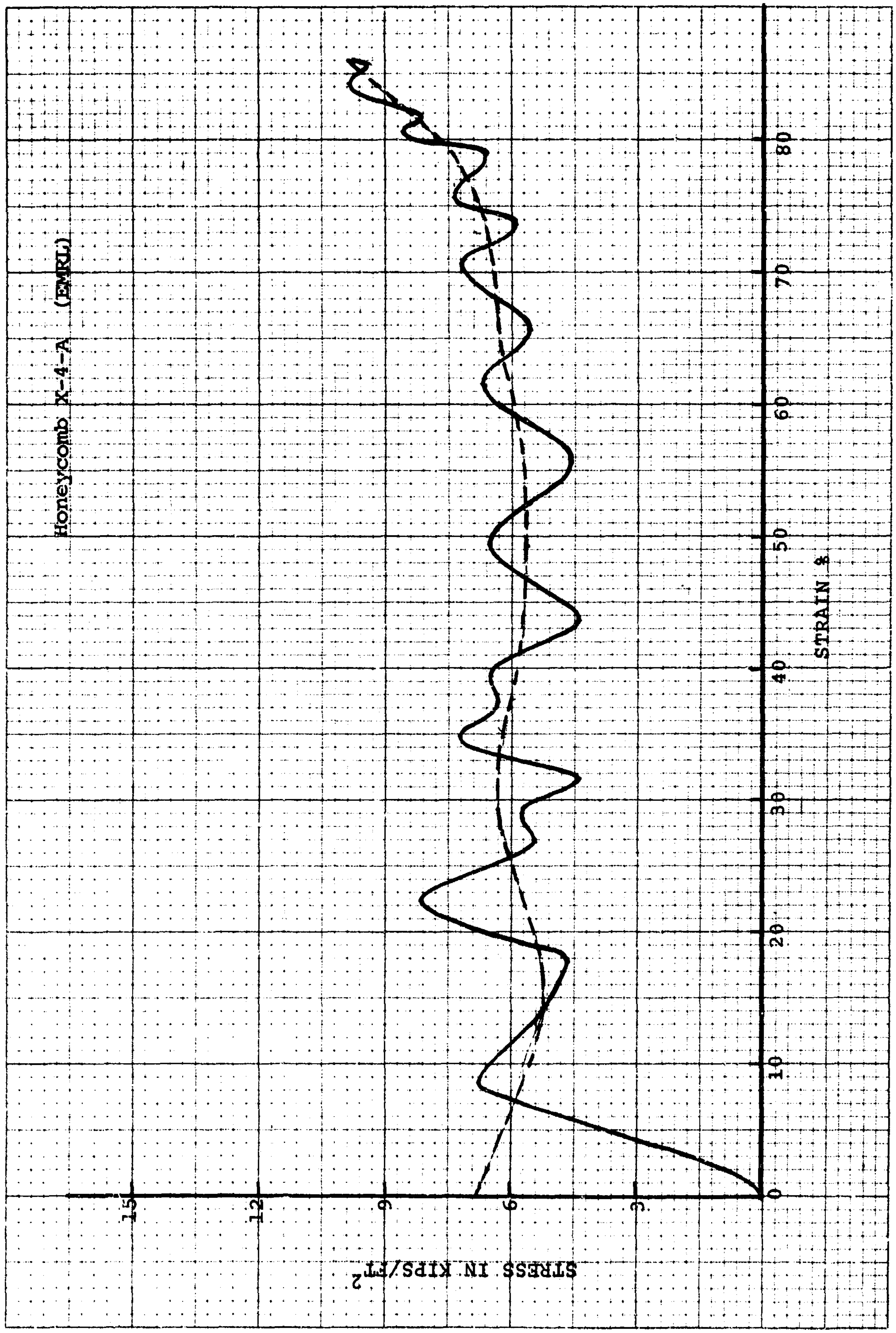
APPENDIX II

STRESS-STRAIN CURVES FOR ALL TESTS


Honeycomb X-1-A (EMRL)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT2
3
6
9
12
15


Honeycomb X-3-A (EMRL)
STRAIN %
STRESS IN KIPS/FT^2
0
10
20
30
40
50
60
70
80
3
6
9
12
15


Honeycomb X-3-B (EMRL)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
50
60
70
80
3
6
9
12
15


Honeycomb X-4-A (EMRL)
STRAIN %
STRESS IN KIPS/FT^2
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20
30
40
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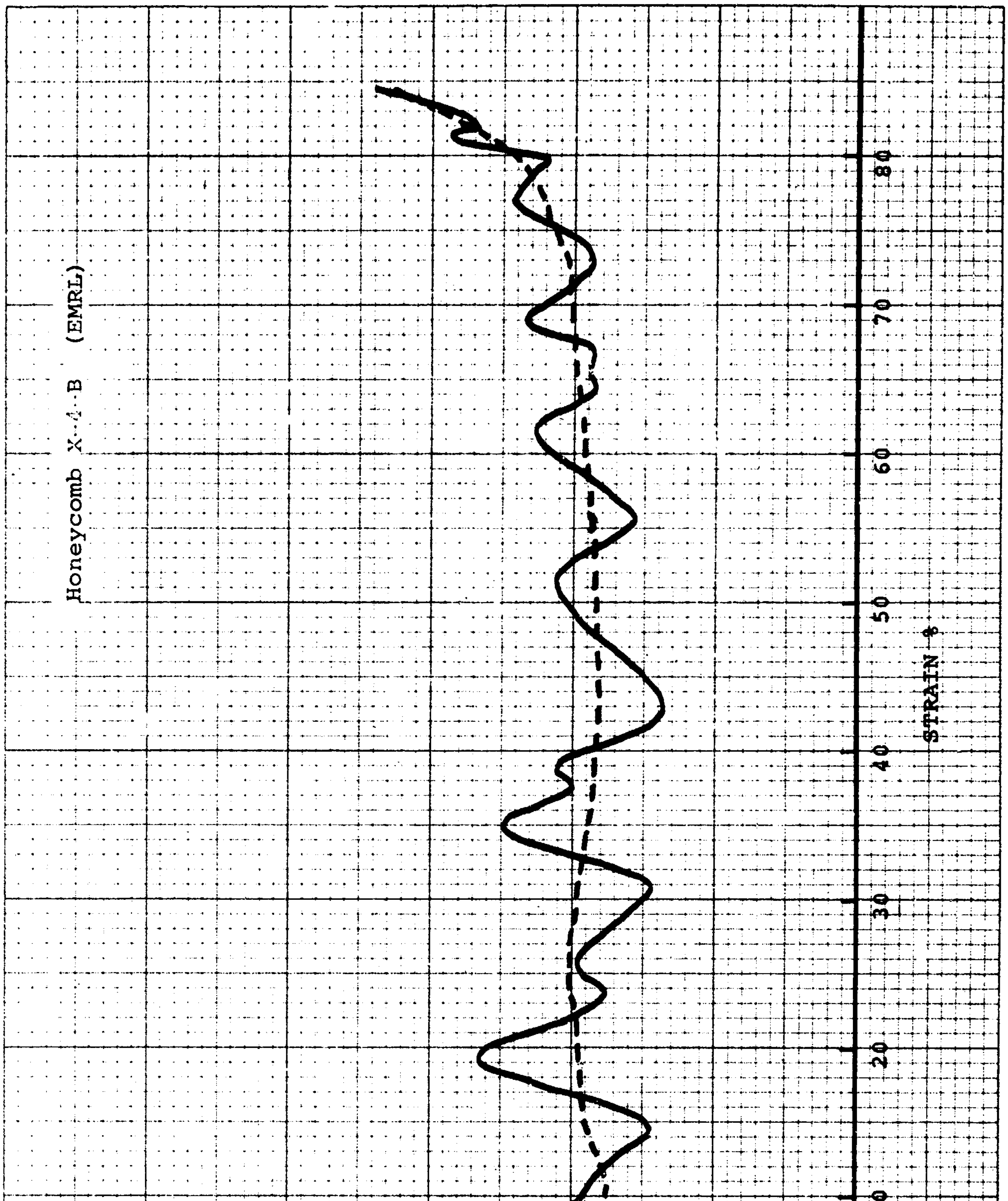
60
70
80
3
6
9
12
15


Honeycomb X-4-B (EMRL)
STRESS IN KIPS/FT²
STRAIN %
16
14
12
10
8
6
4
2
0
10
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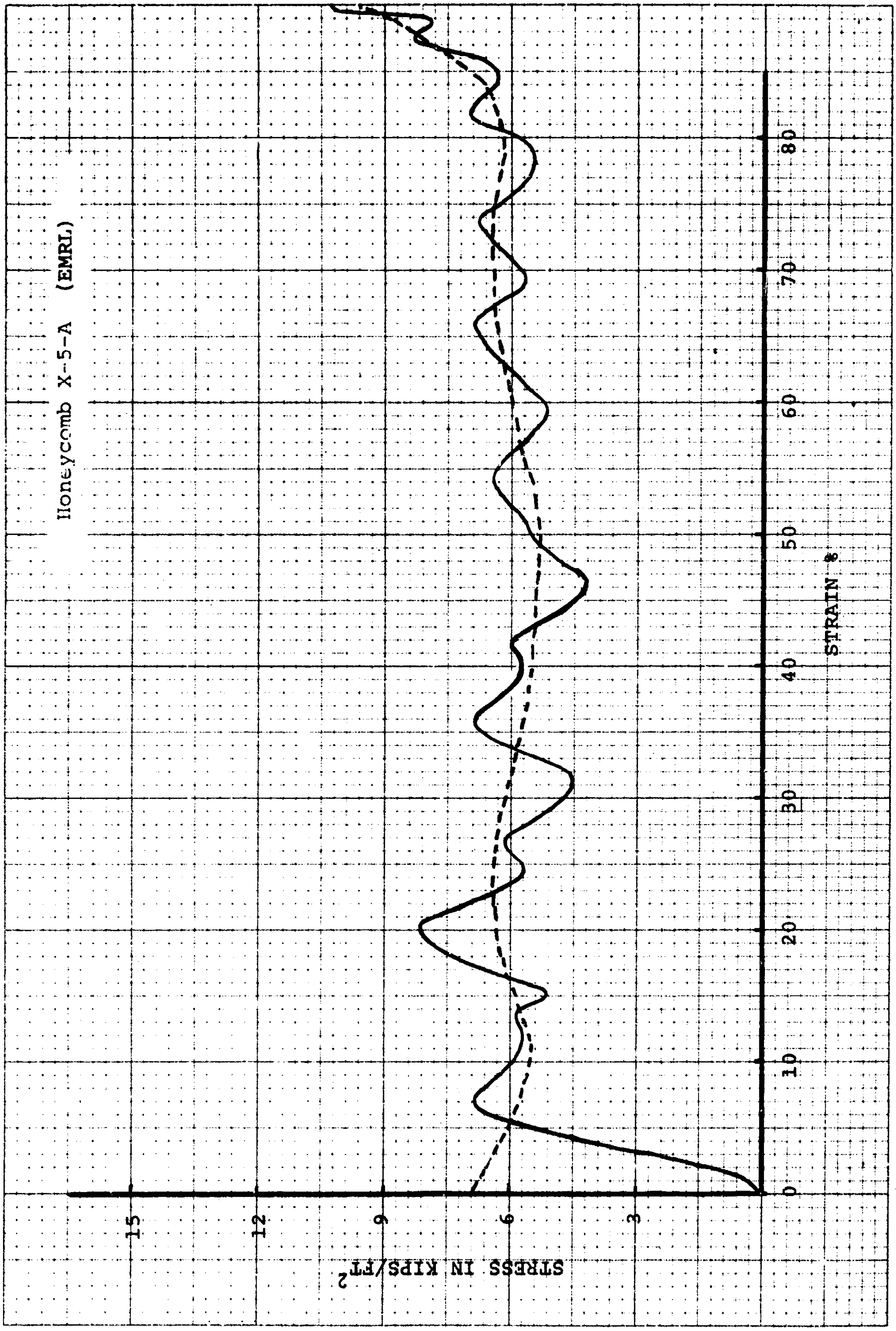
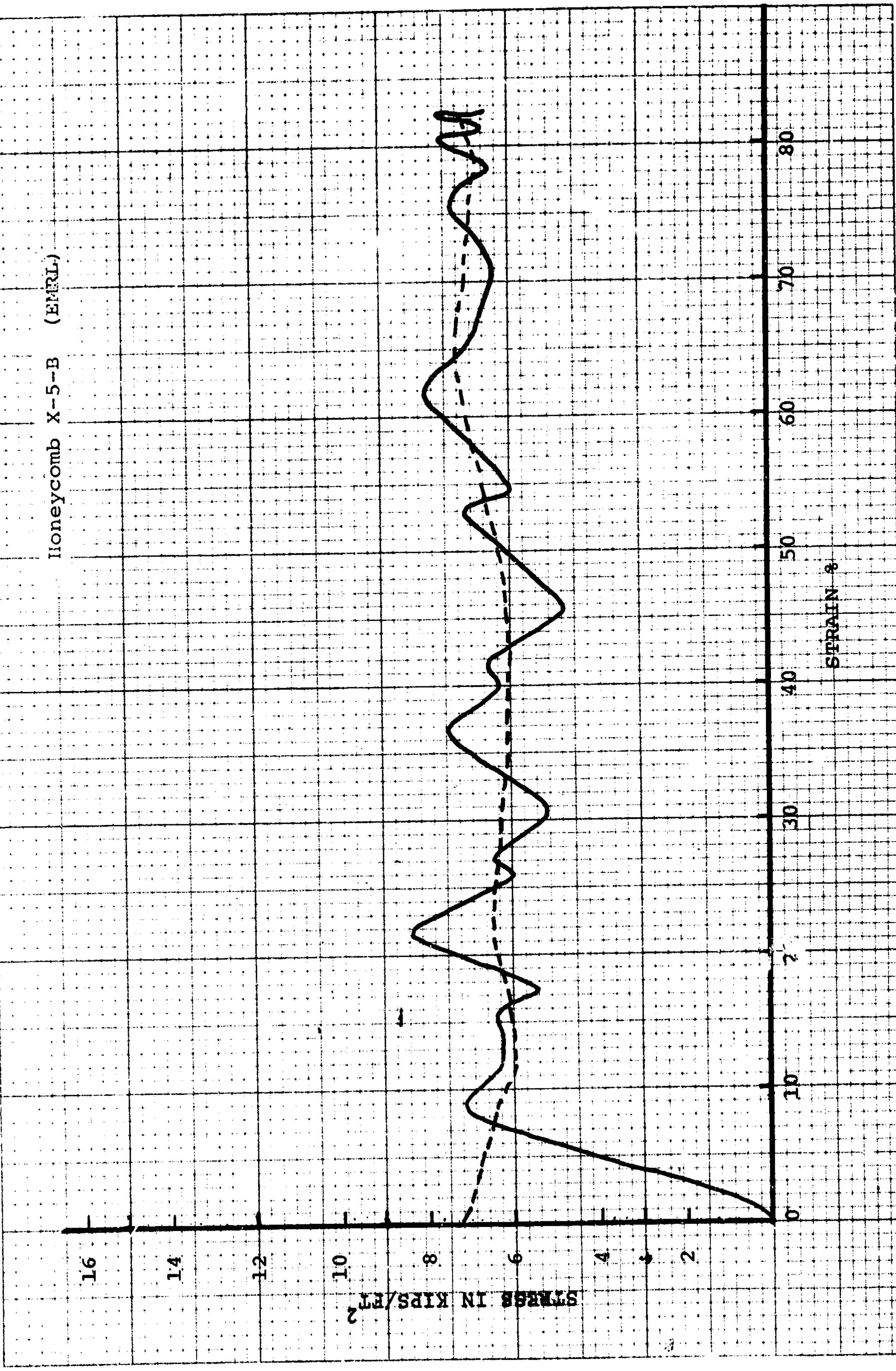
40
50
60
70
80


Honeycomb X-5-A (EMRL)
STRESS IN KIPS/FT²
15
12
9
6
3
STRAIN %
0
10
20
30
40
50
60
70
80


Honeycomb X-5-B (EMRL)
STRAIN %
STRESS IN KIPS/FT^2
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20
30
40
50
60
70
80
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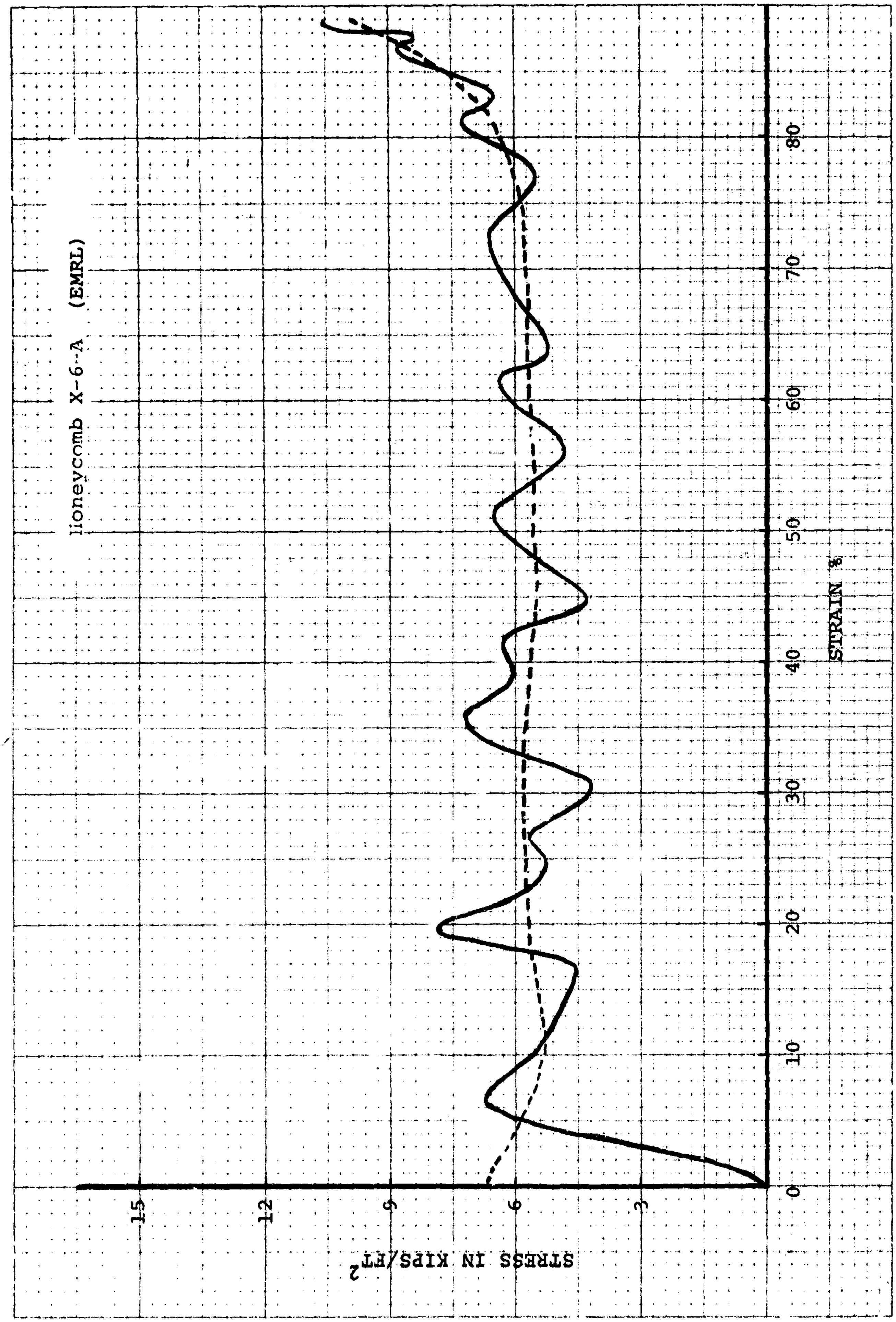
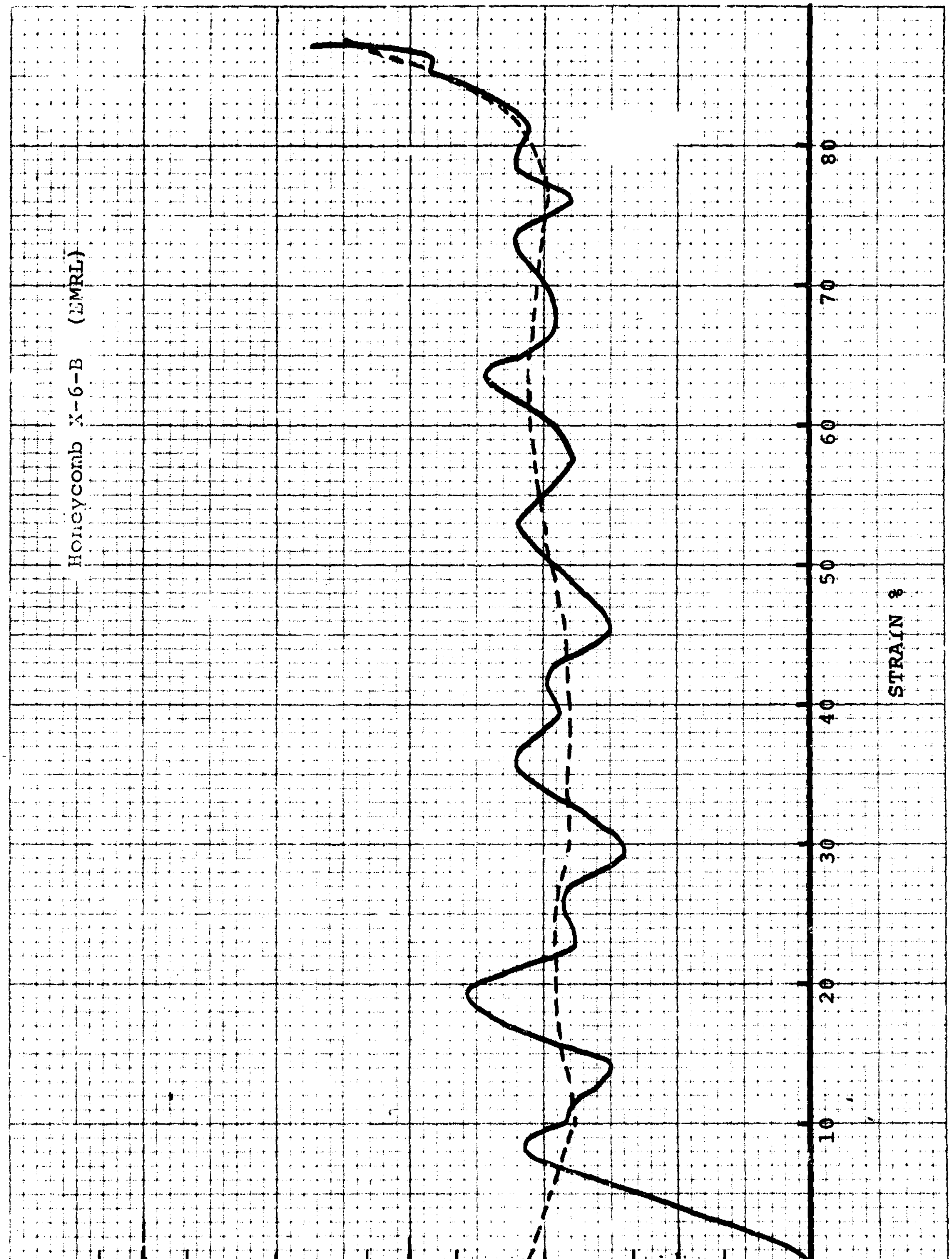
6
8
10
12
14
16


Honeycomb X-6-A (EMRL)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
50
60
70
80
3
6
9
12
15


Honeycomb X-6-B (EMRL)
STRAIN %
STRESS IN KIPS/FT^2
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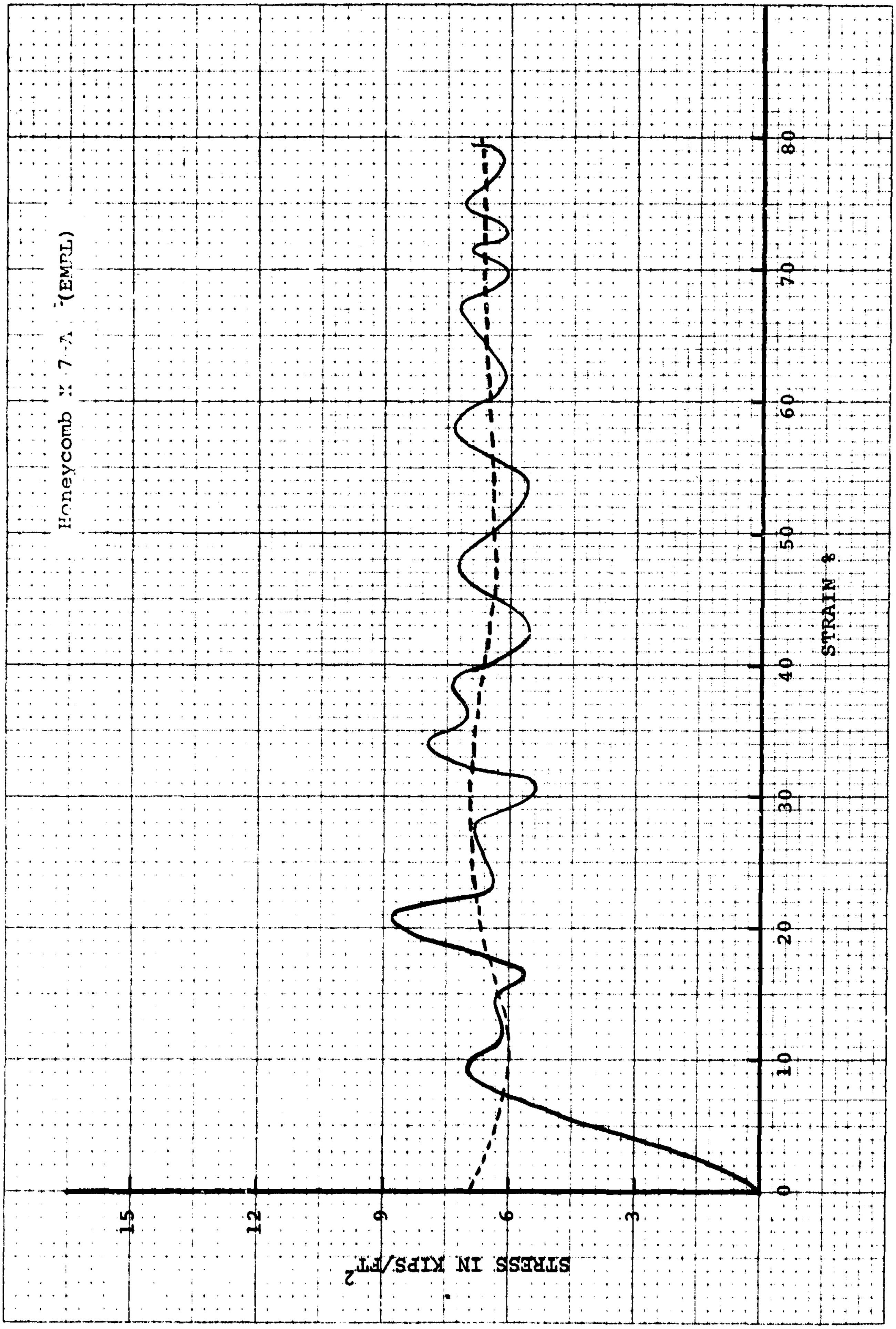
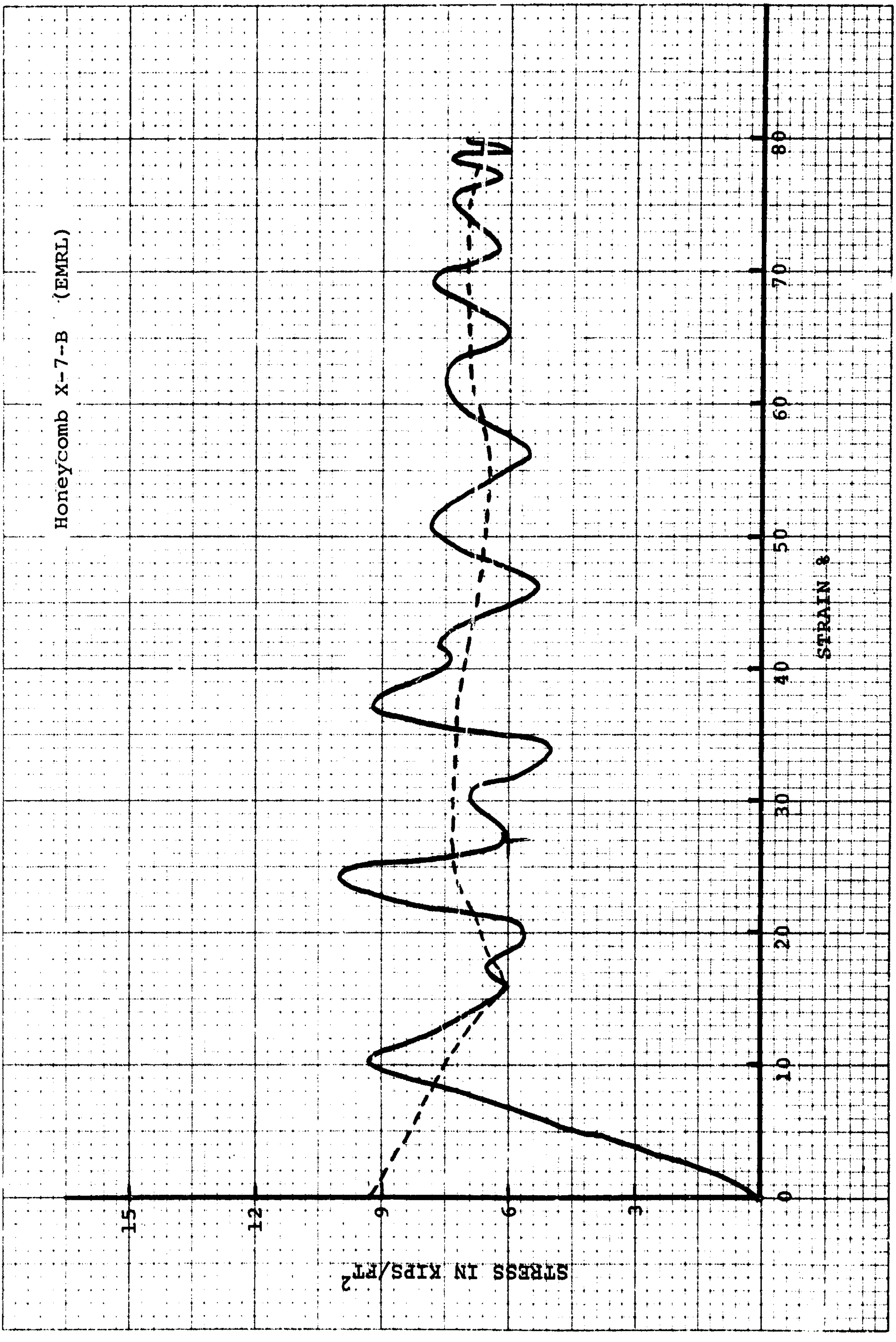
8
10
12
14
16


Honeycomb
(EMPL)
STRESS IN KIPS/FT²
15
12
9
6
3
0
10
20
30
40
50
60
70
80
STRAIN %


Honeycomb X-7-B (EMRL)
STRESS IN KIPS/FT^2
STRAIN %
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3
6
9
12
15
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20
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60
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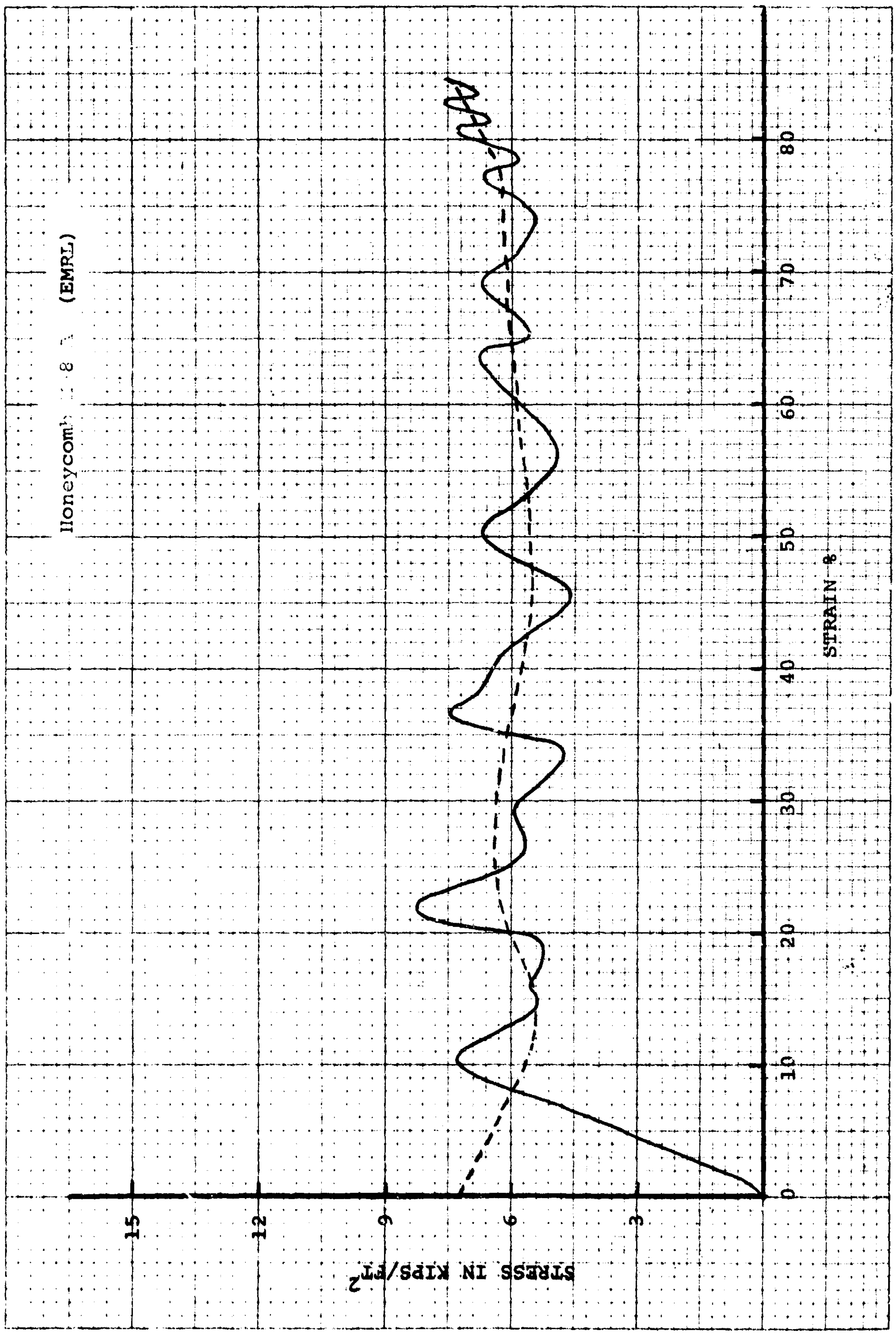
80


Honeycomb
(EMRL)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
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60
70
80
3
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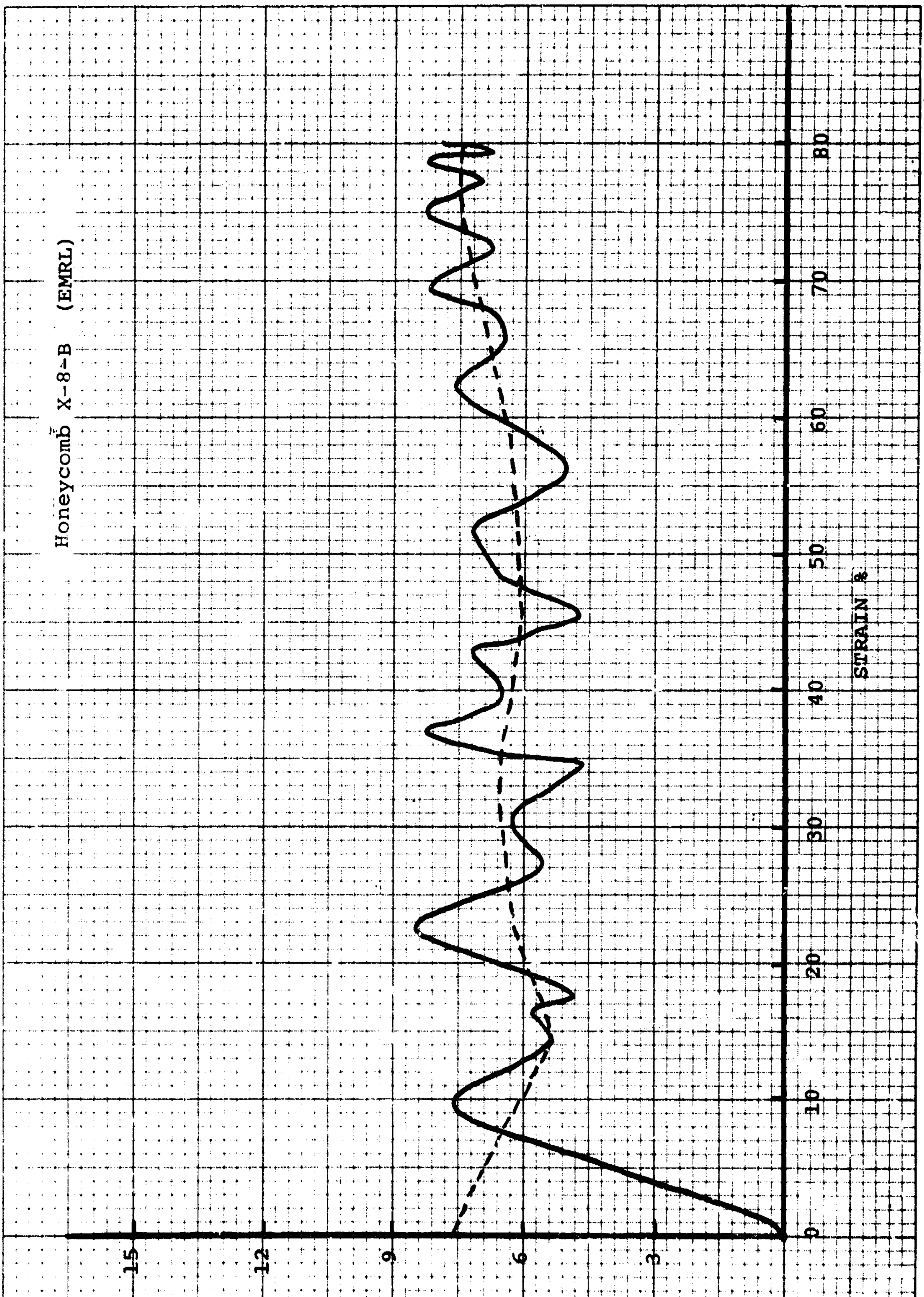
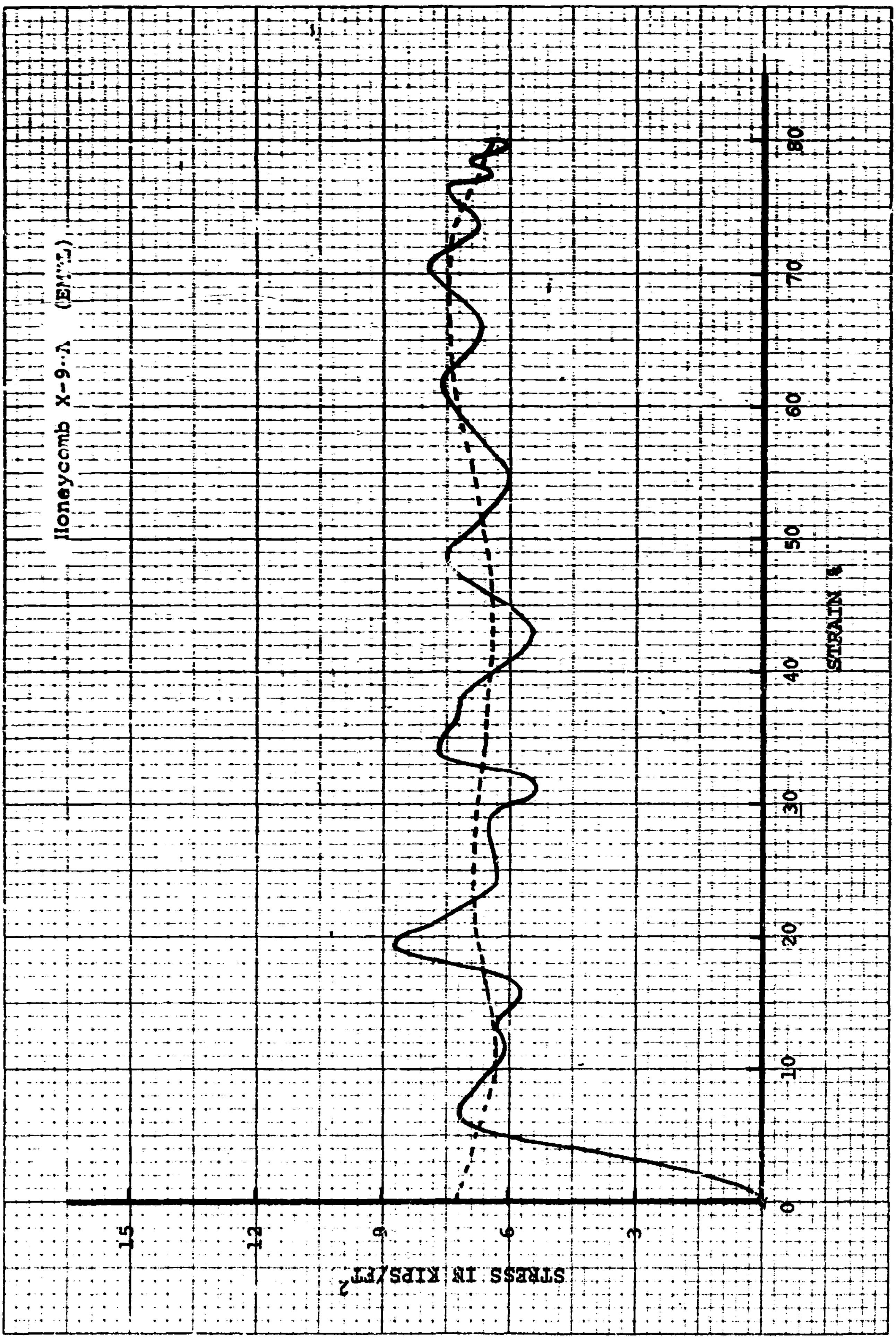
9
12
15


Honeycomb X-8-B (EMRL)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT2
3
6
9
12
15


Honeycomb X-9-A
STRESS IN KIPS/FT²
STRAIN %
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3
6
9
12
15
10
20
30
40
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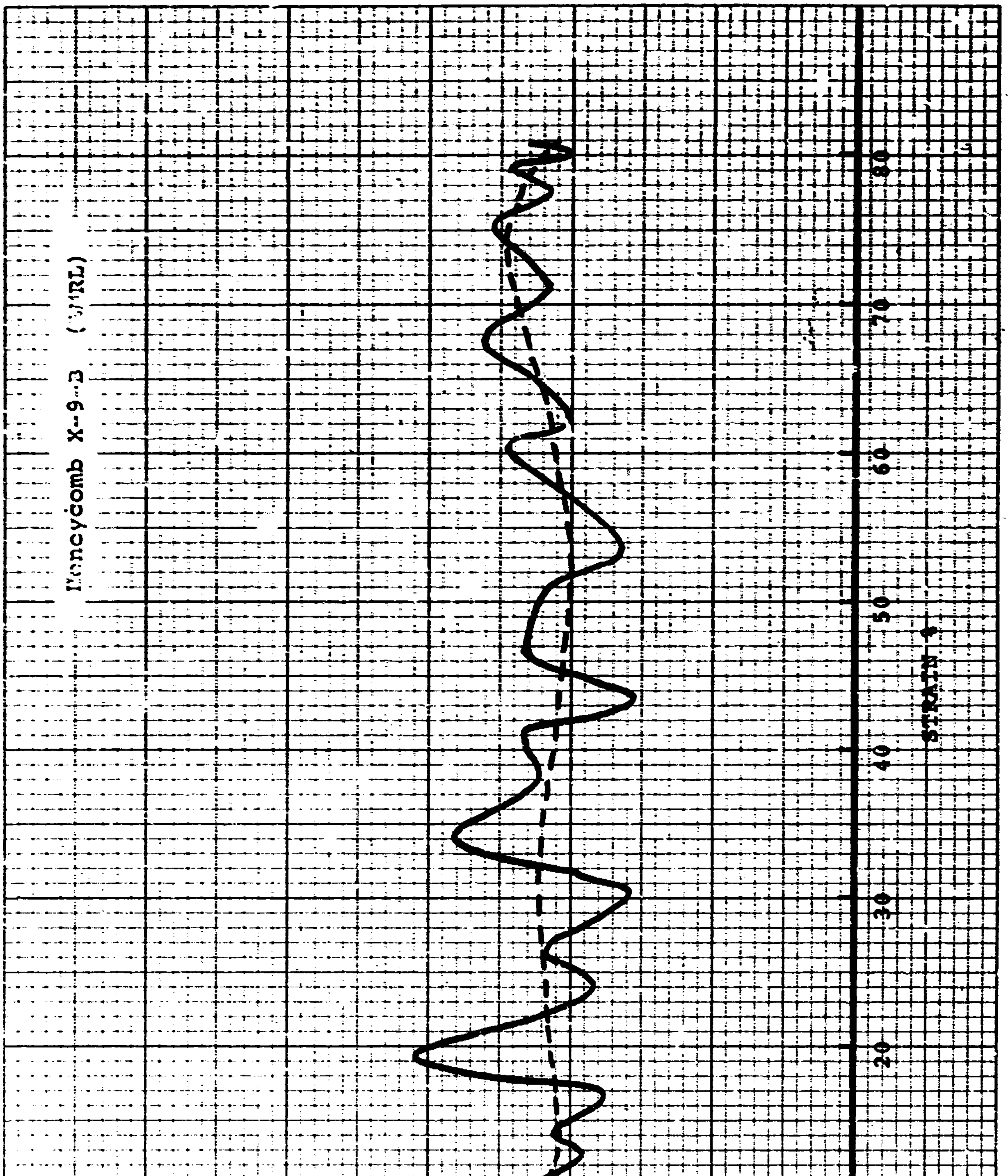
60
70
80



Honeycomb X-9-3
STRESS IN KIPS/FT²
STRAIN %
0
10
20
30
40
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70
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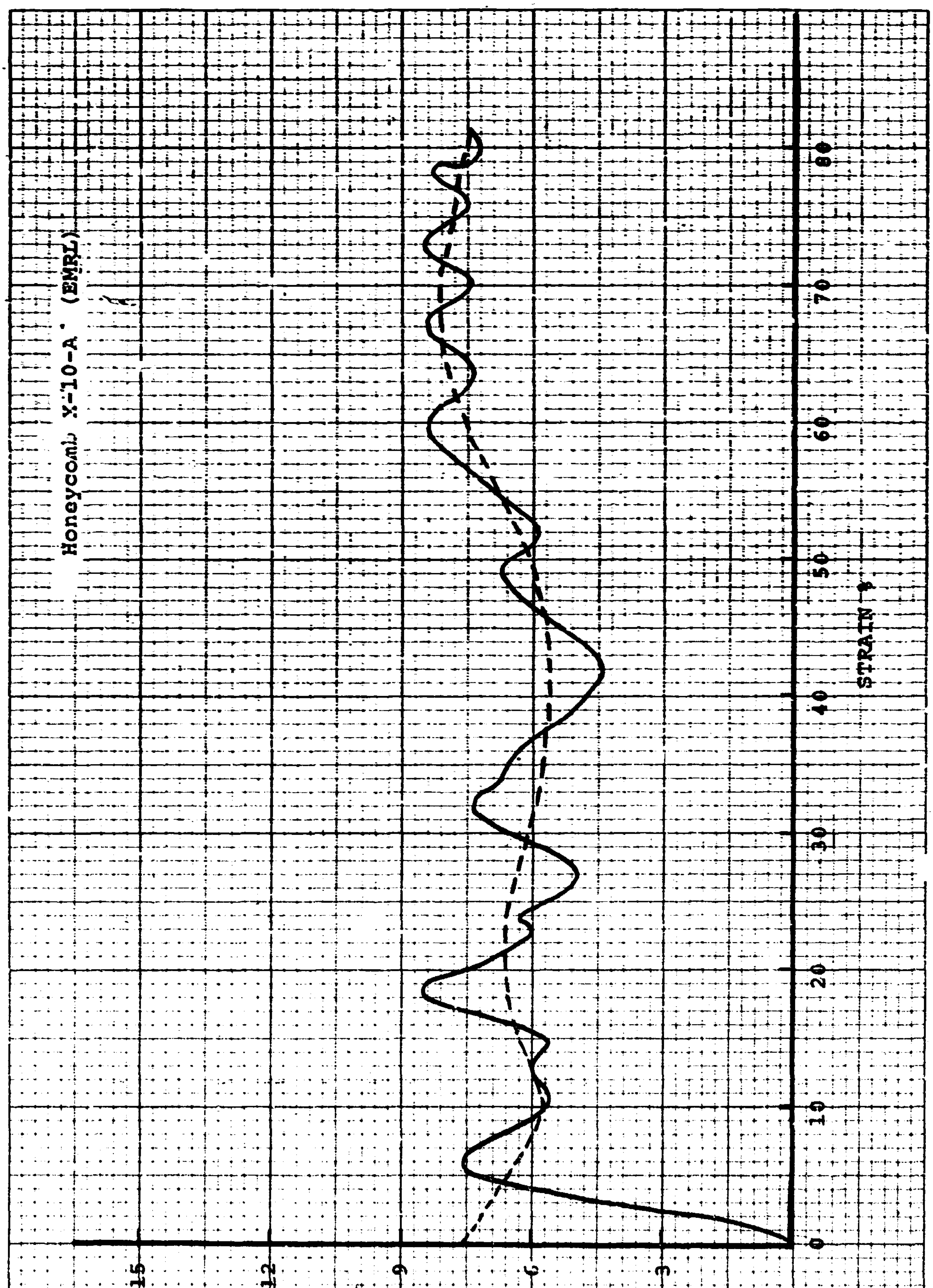
12
15


Honeycomb X-10-A (EMRL)
STRAIN %
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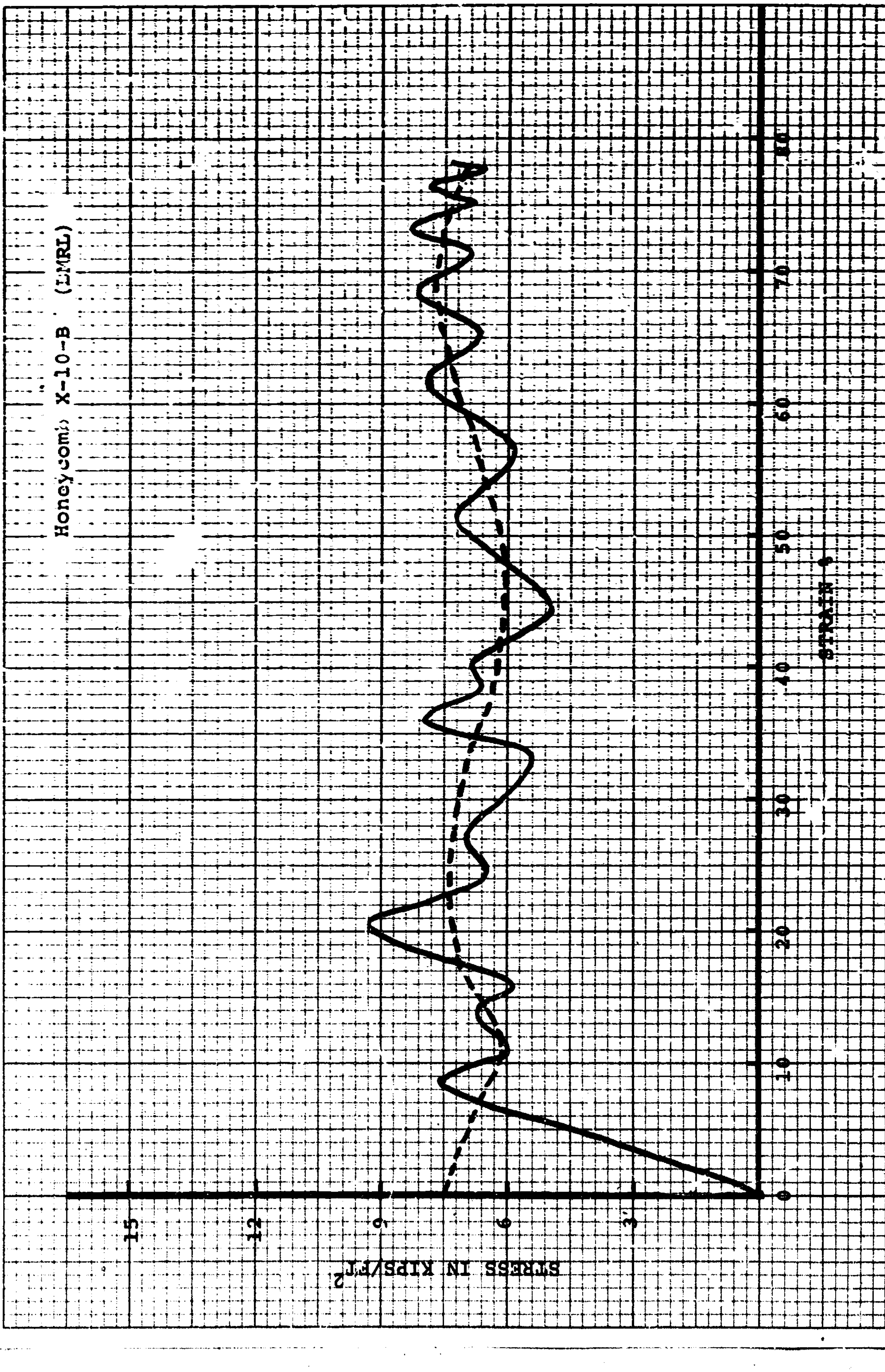
20
30
40
50
60
70
80
STRESS IN KIPS/FT^2
3
6
9
12
15


Honeycomb X-10-B (LMRL)
STRESS IN KIPS/FT²
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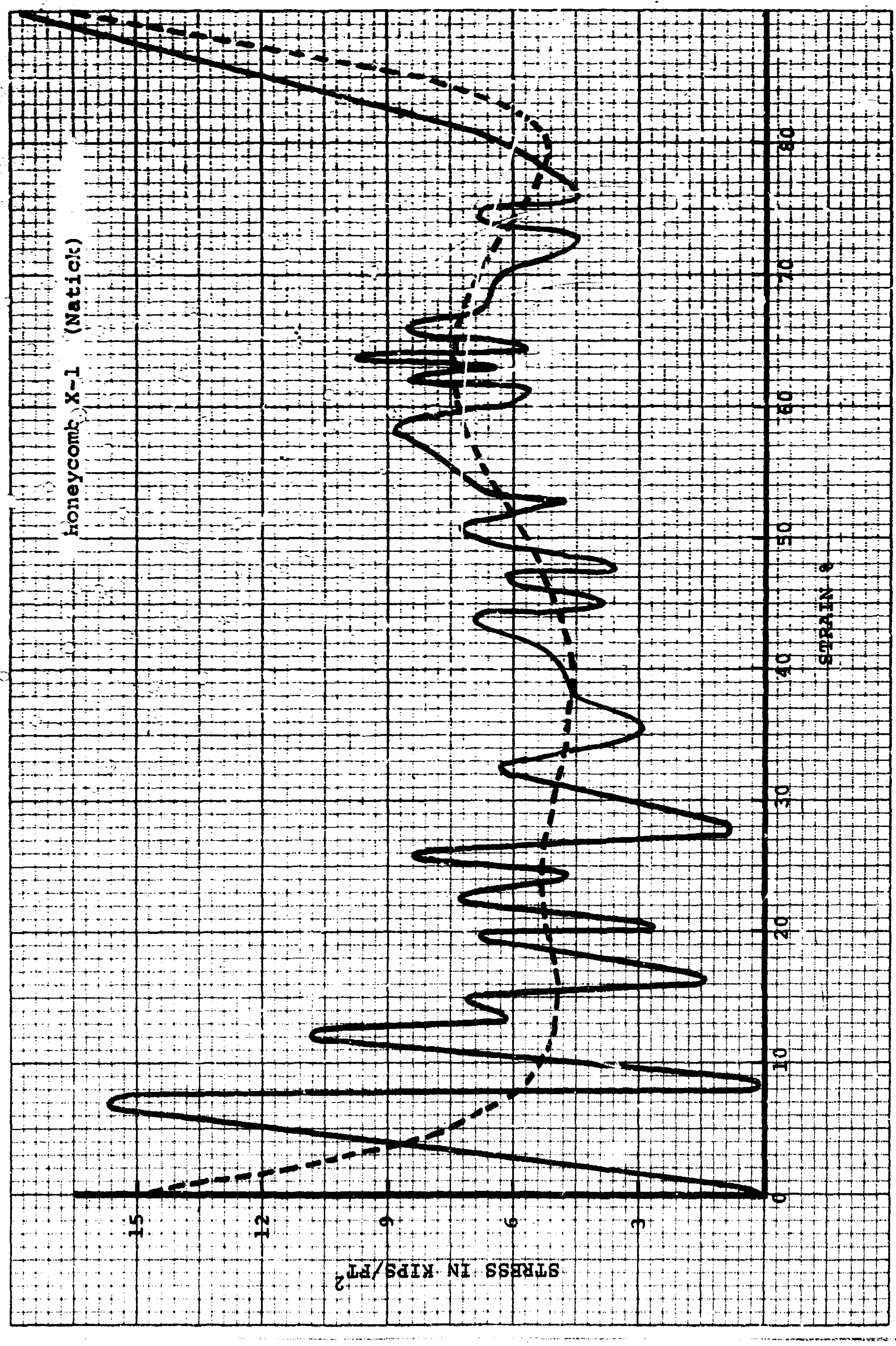
12
9
6
3
0
10
20
30
40
50
60
70
80
STRAIN %


Honeycomb X-1 (Natick)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
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80
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6
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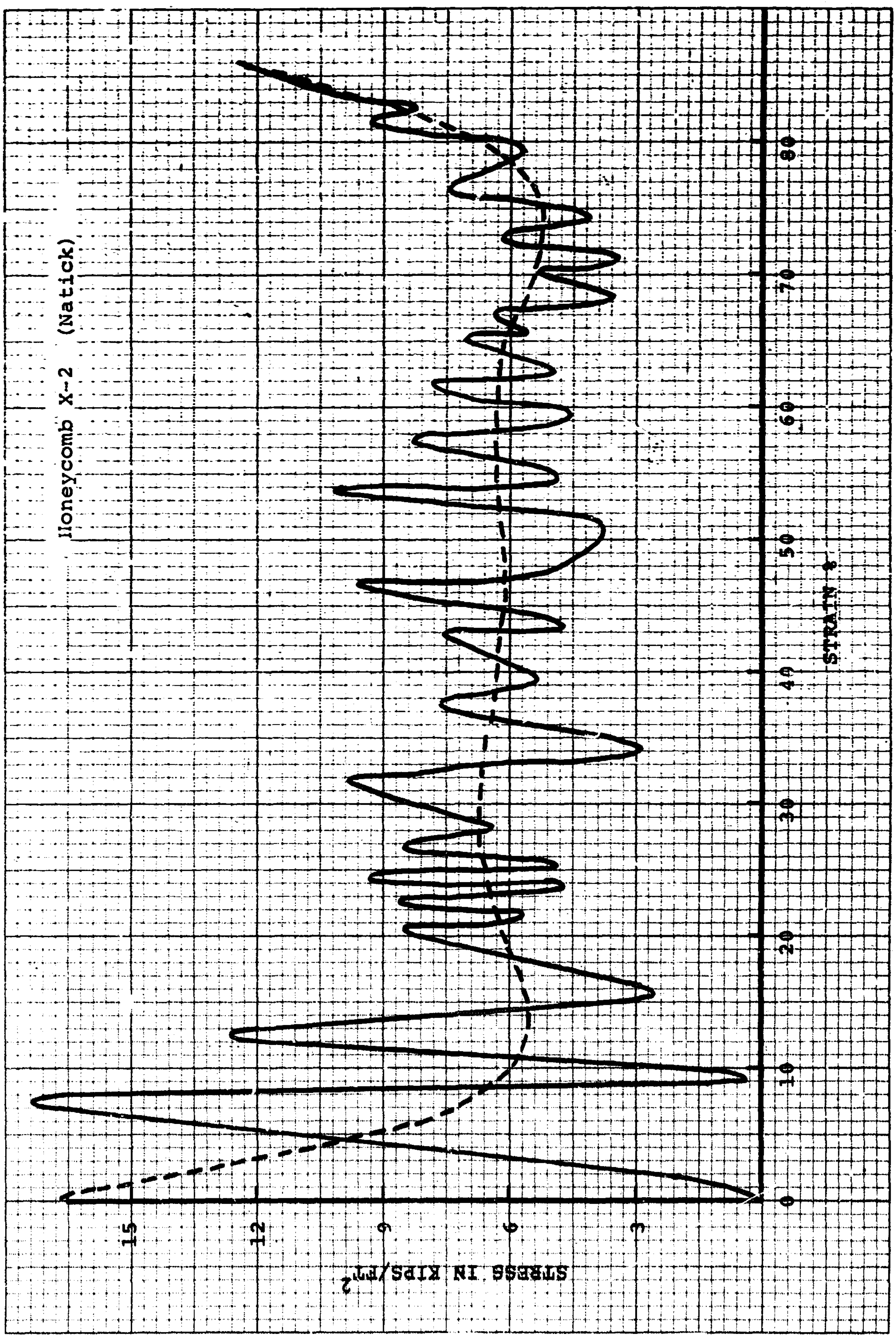
12
15


Honeycomb X-2 (Natick)
STRAIN %
STRESS IN KIPS/FT²
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30
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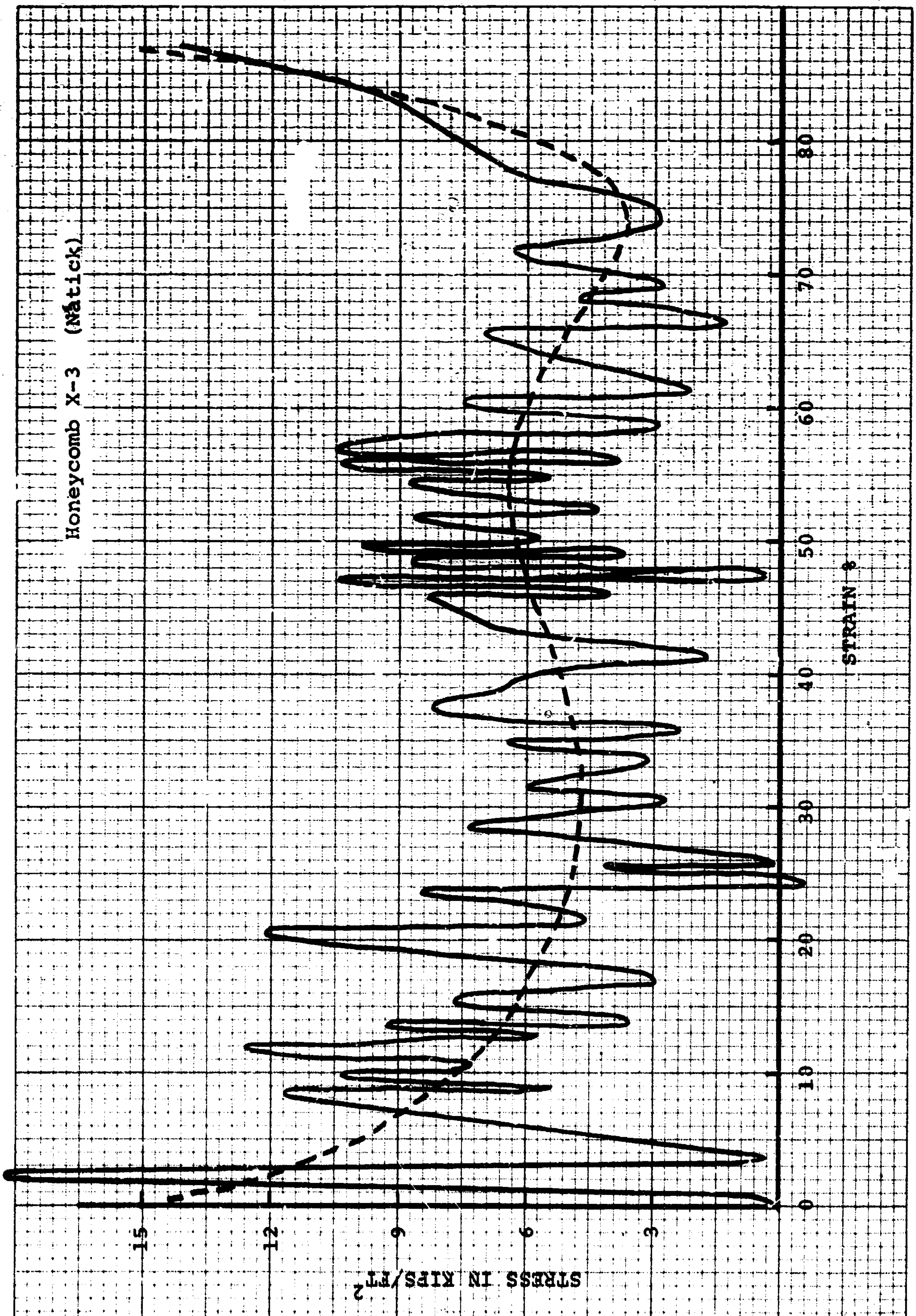
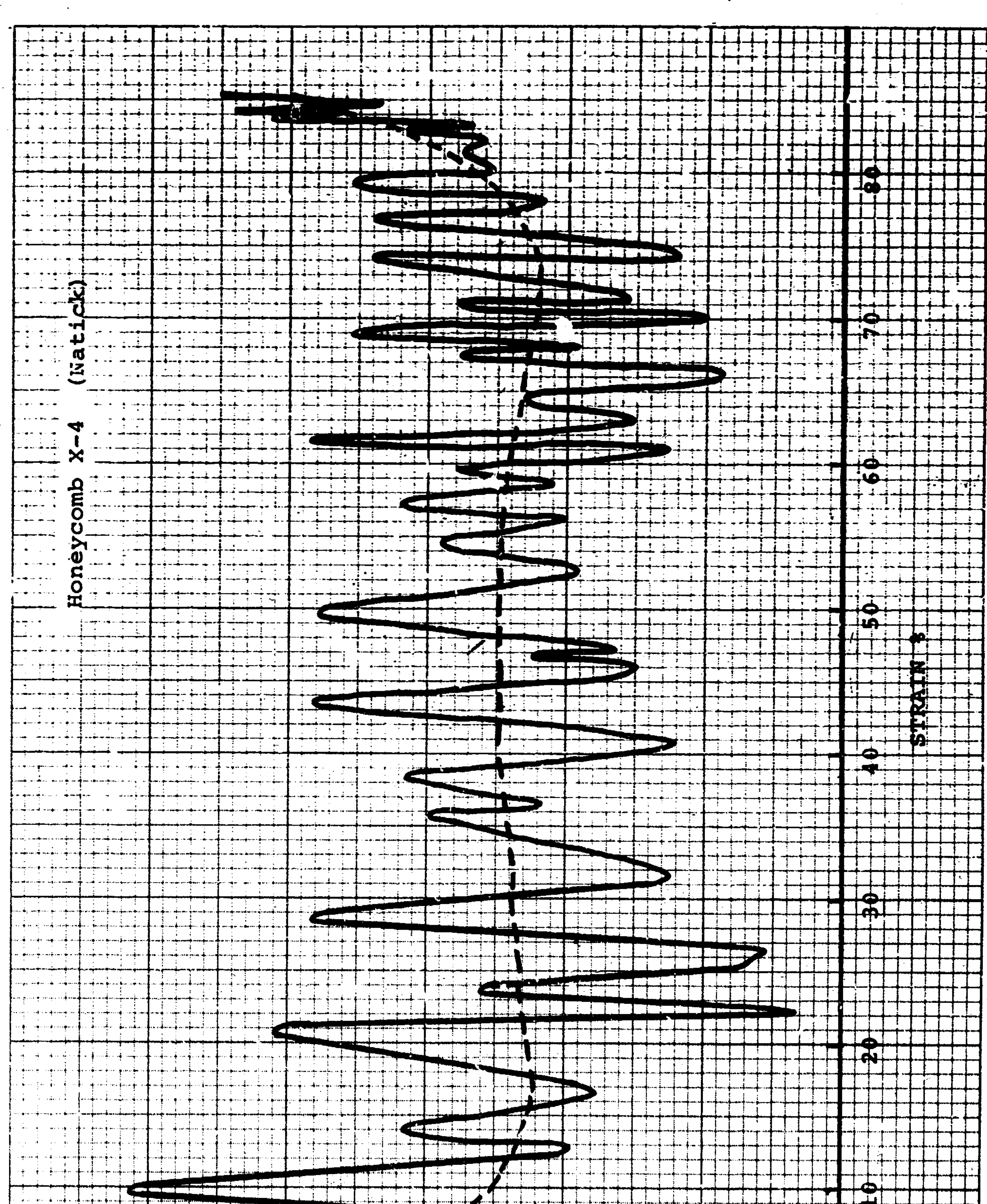
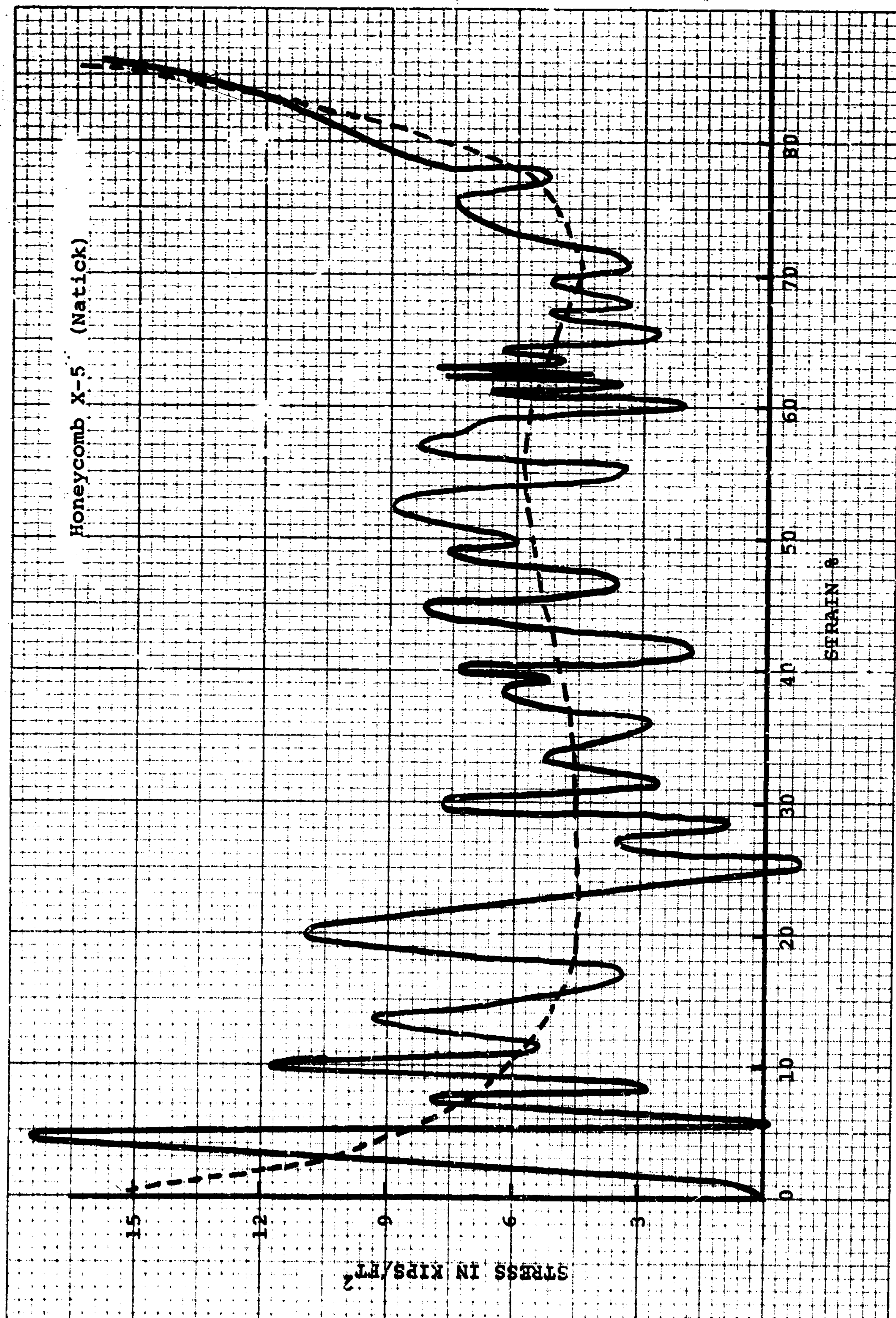
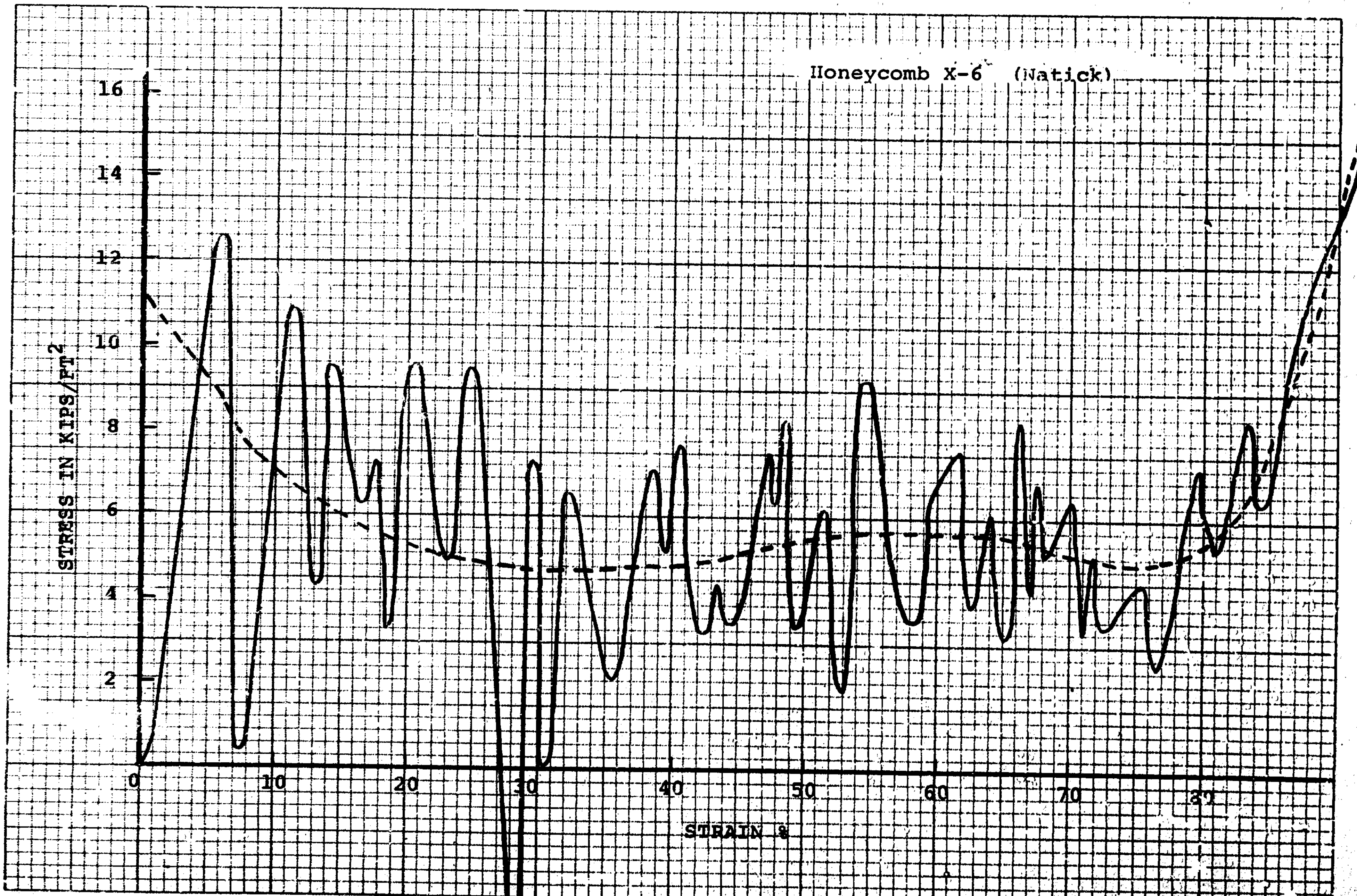
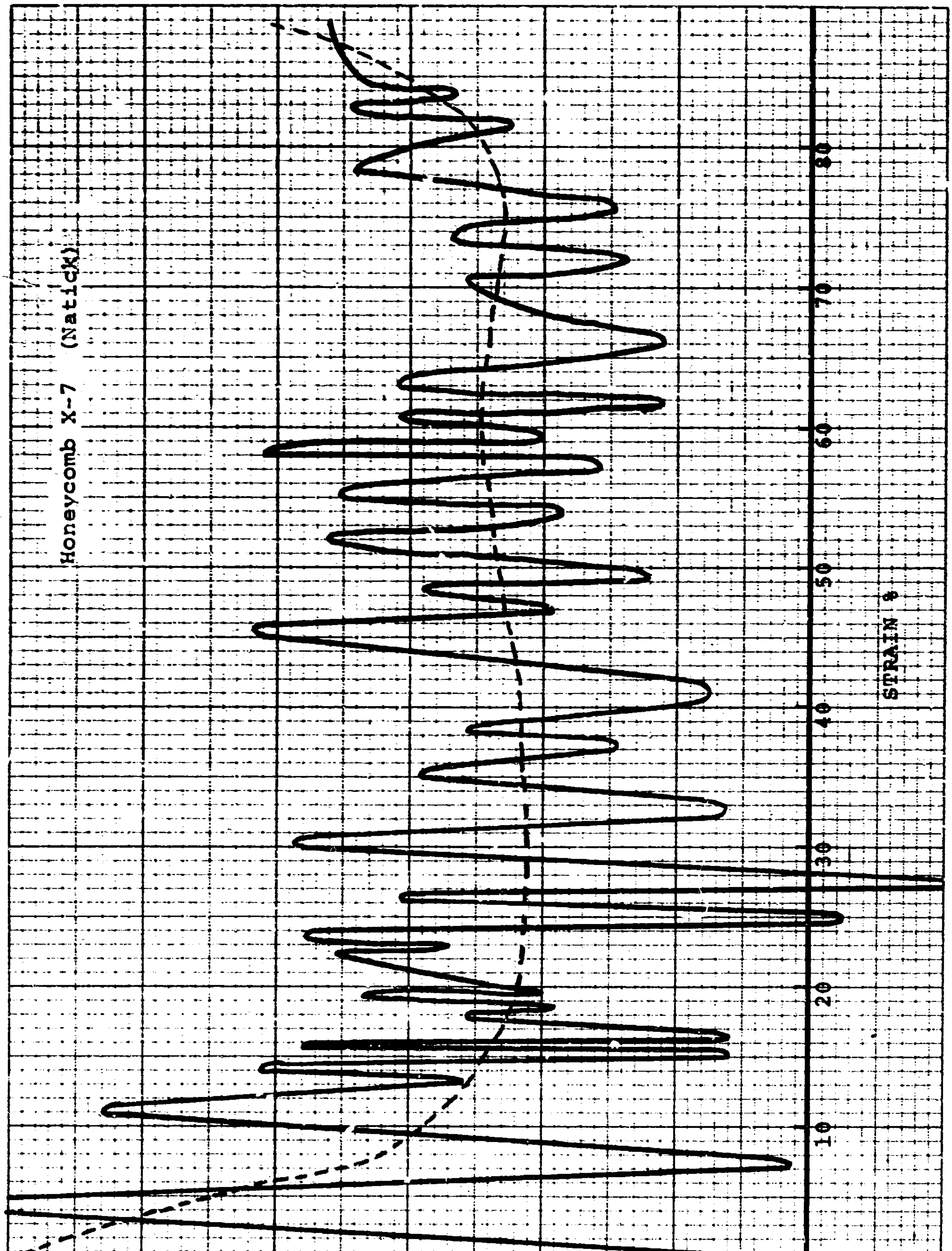
70
80
3
6
9
12
15


Honeycomb X-3 (Natick)
STRESS IN KIPS/FT2
STRAIN %
0
10
20
30
40
50
60
70
80
3
6
9
12
15

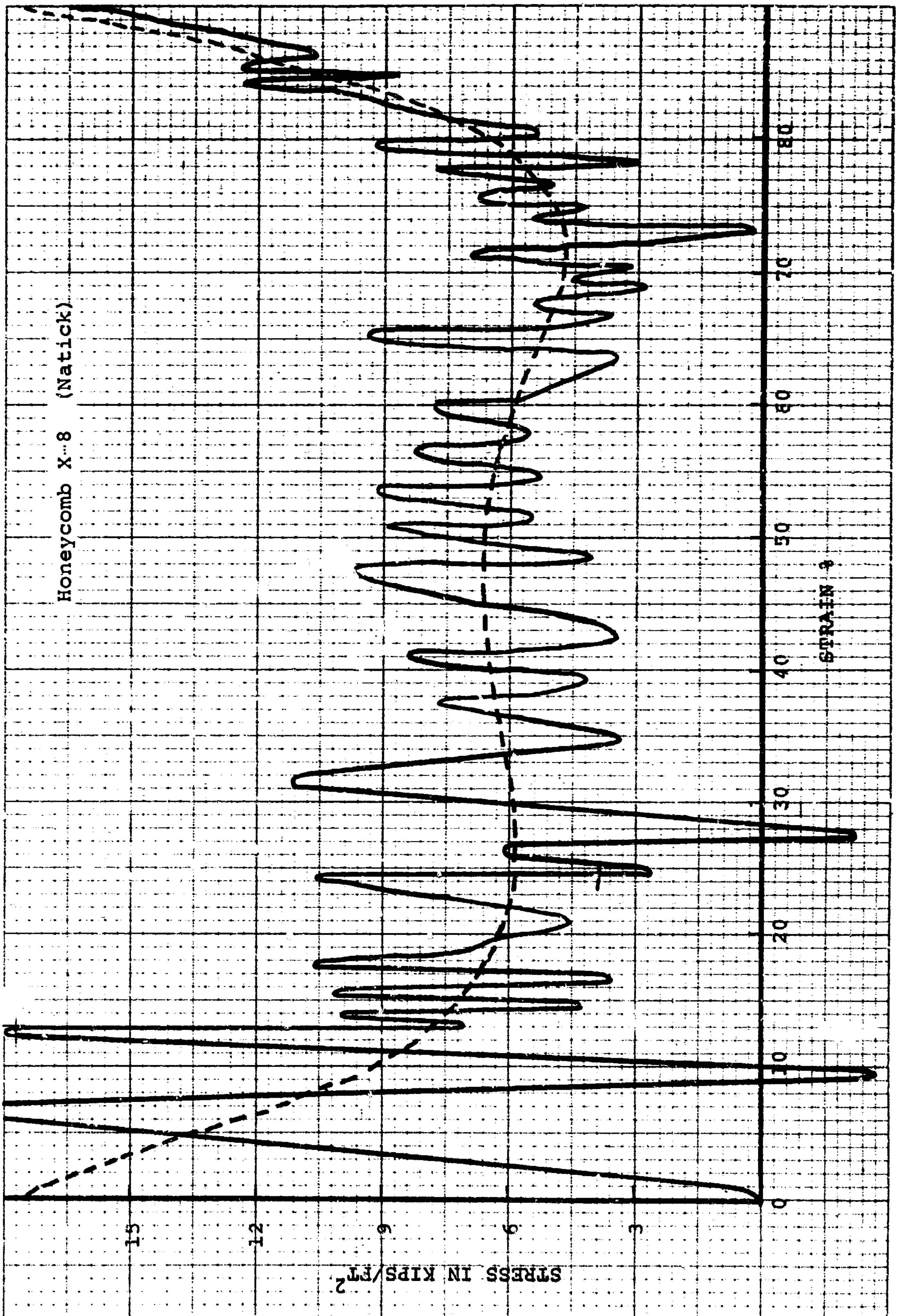

Honeycomb X-4 (Natick)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
50
60
70
80
3
6
9
12
15

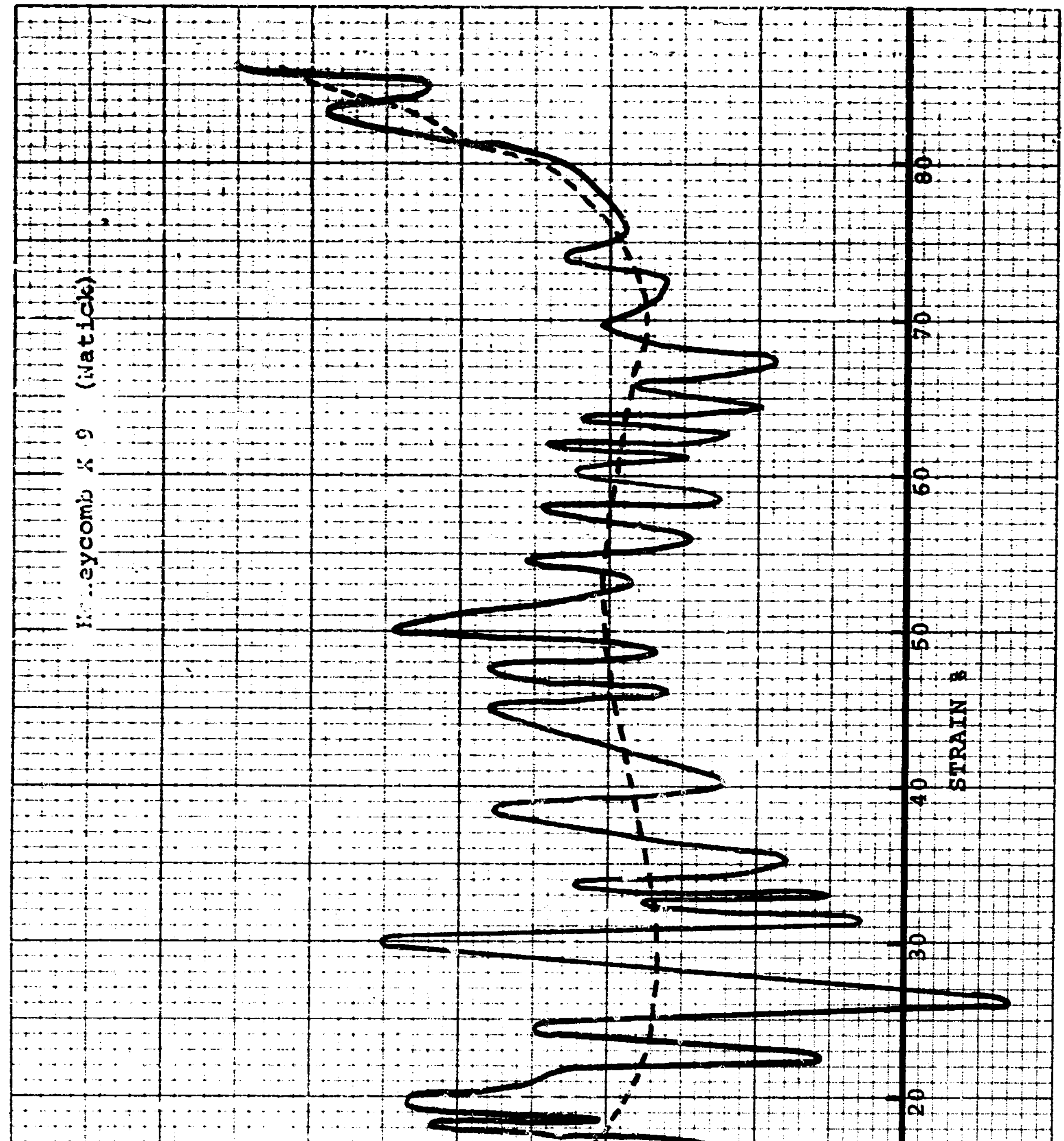

Honeycomb X-5 (Natick)
STRESS IN KIPS/FT²
15
12
9
6
3
STRAIN %
0
10
20
30
40
50
60
70
80

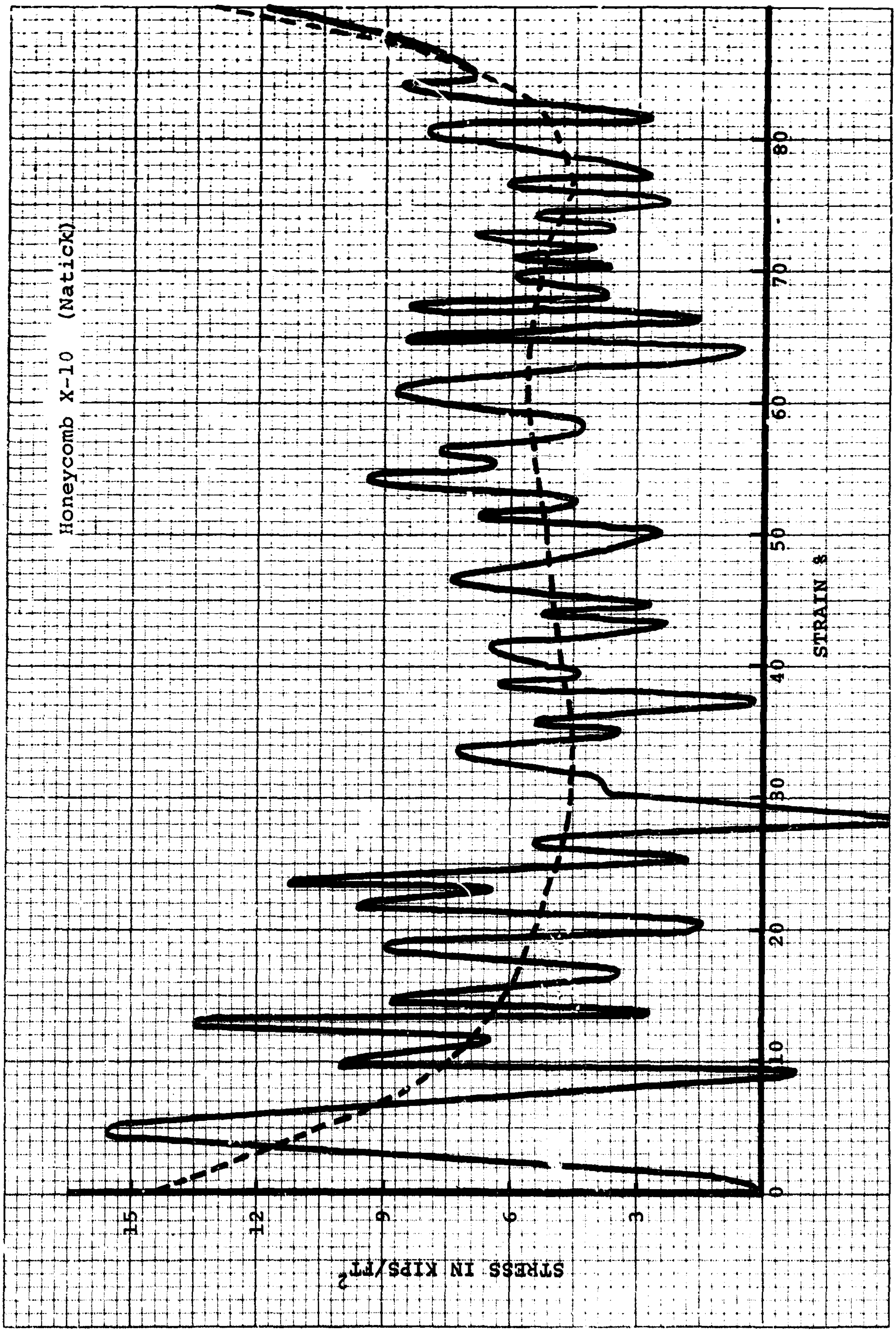

Honeycomb X-6" (Natick)
STRESS IN KIPS/FT^2
STRAIN %
0
10
20
30
40
50
60
70
80
2
4
6
8
10
12
14
16

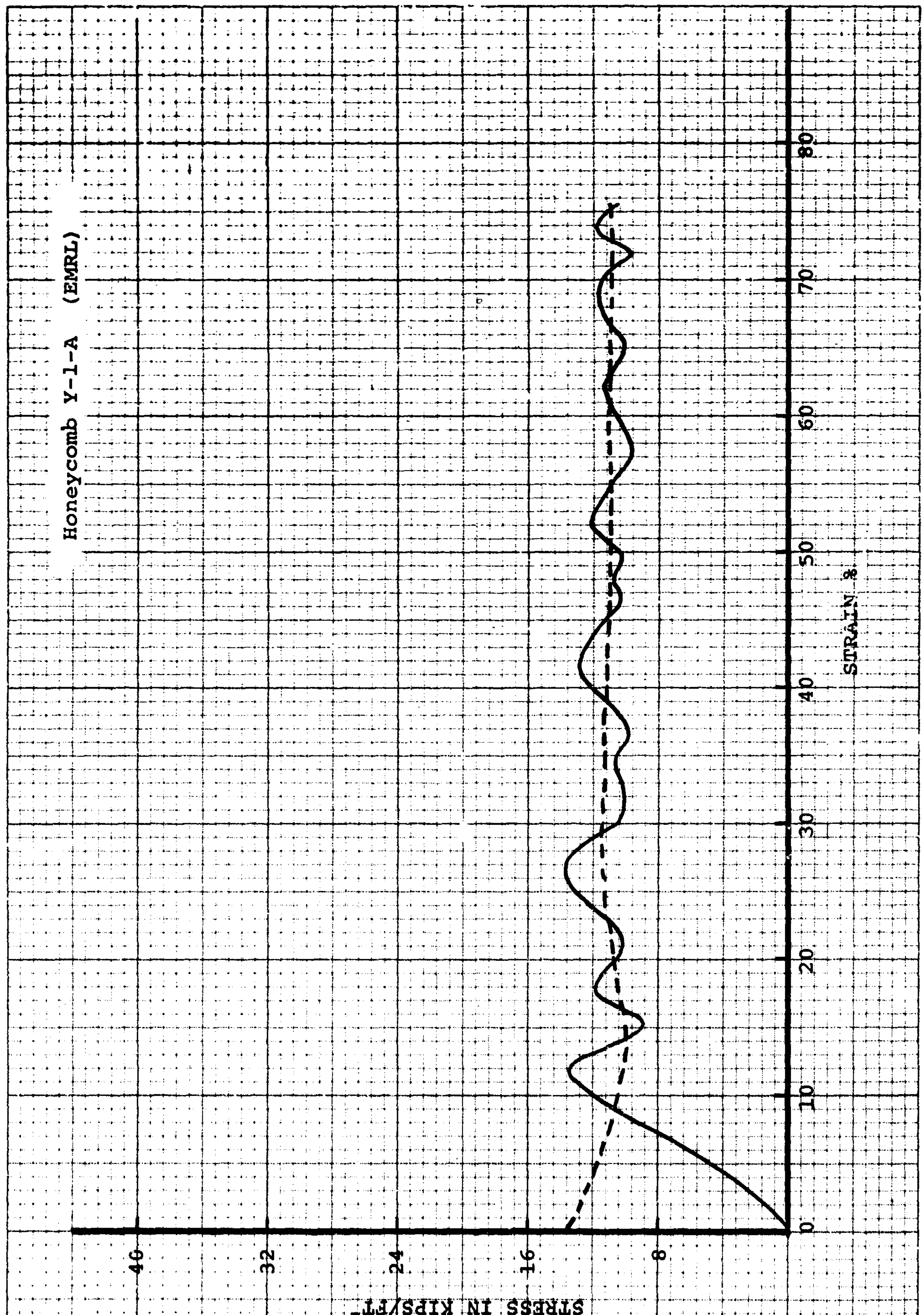


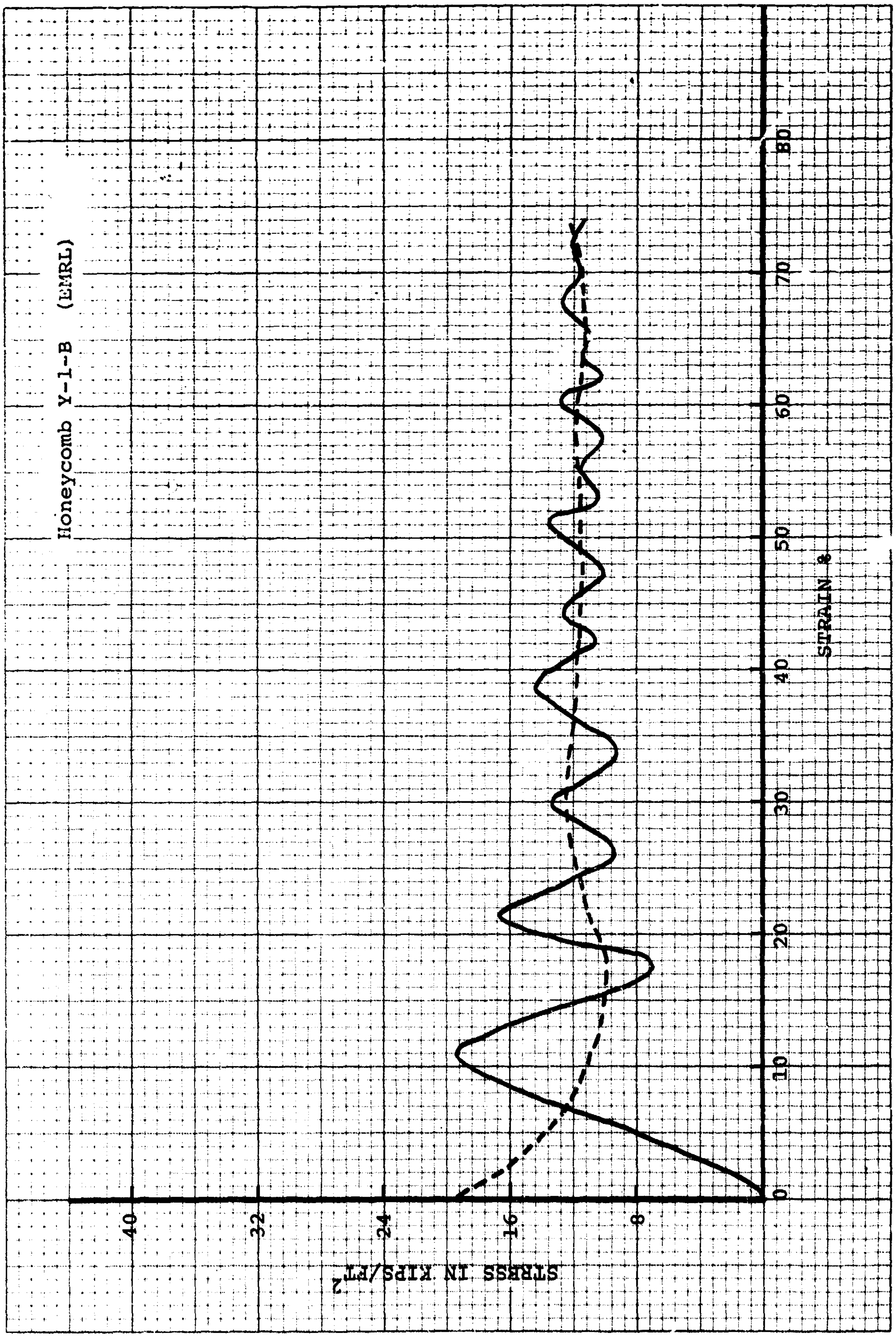
Honeycomb X-7 (Natick)
STRESS IN KIPS/FT²
STRAIN %
16
14
12
10
8
6
4
2
0
10
20
30
40
50
60
70
80


Honeycomb X-8 (Natick)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
50
60
70
80
3
6
9
12
15

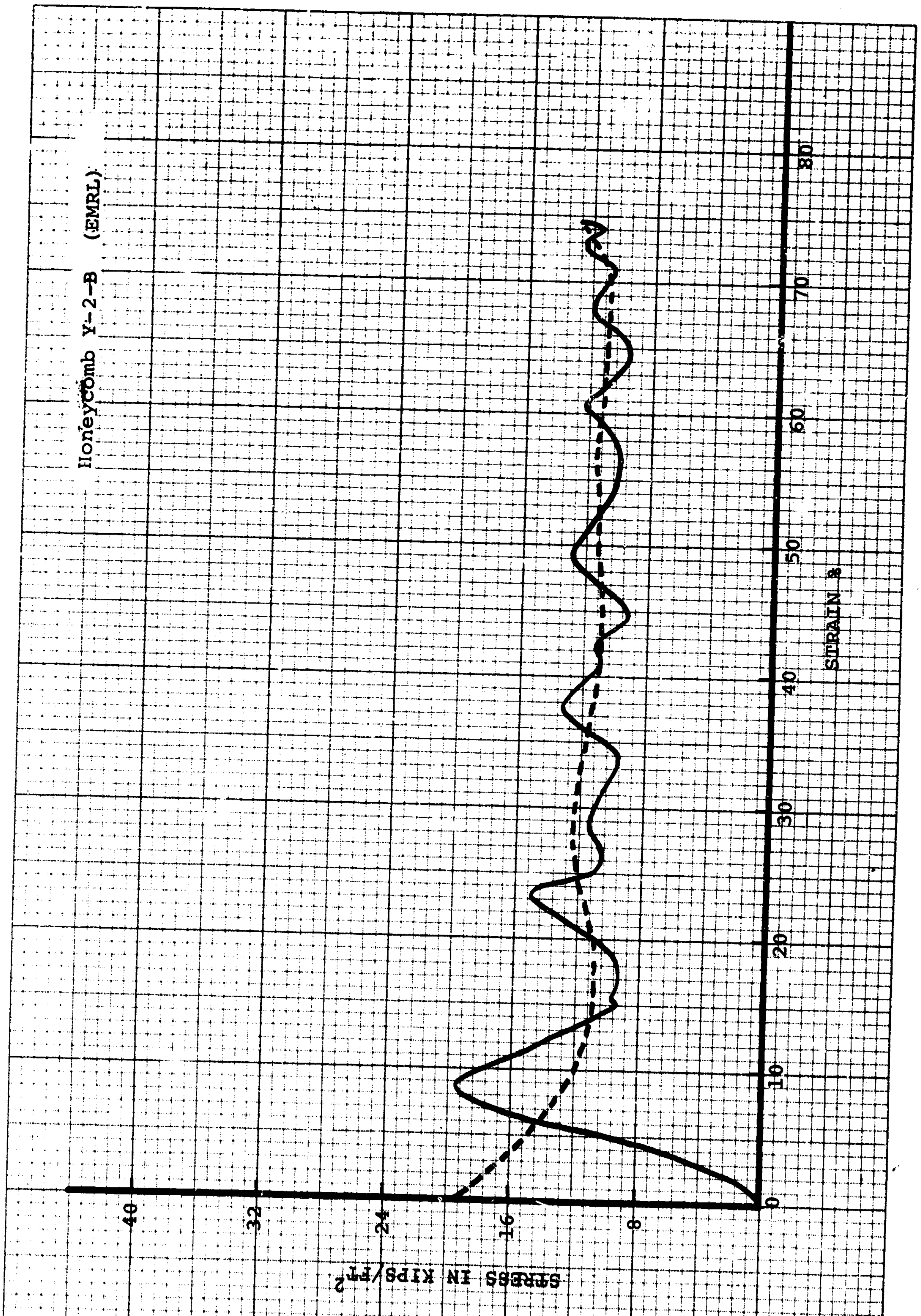

H .eycomb X 9 (Natick)
STRAIN %
STRESS IN KIPS/FT^2
0
10
20
30
40
50
60
70
80
3
6
9
12
15


Honeycomb X-10 (Natick)
STRAIN %
STRESS IN KIPS/FT2
0
10
20
30
40
50
60
70
80
15
12
9
6
3

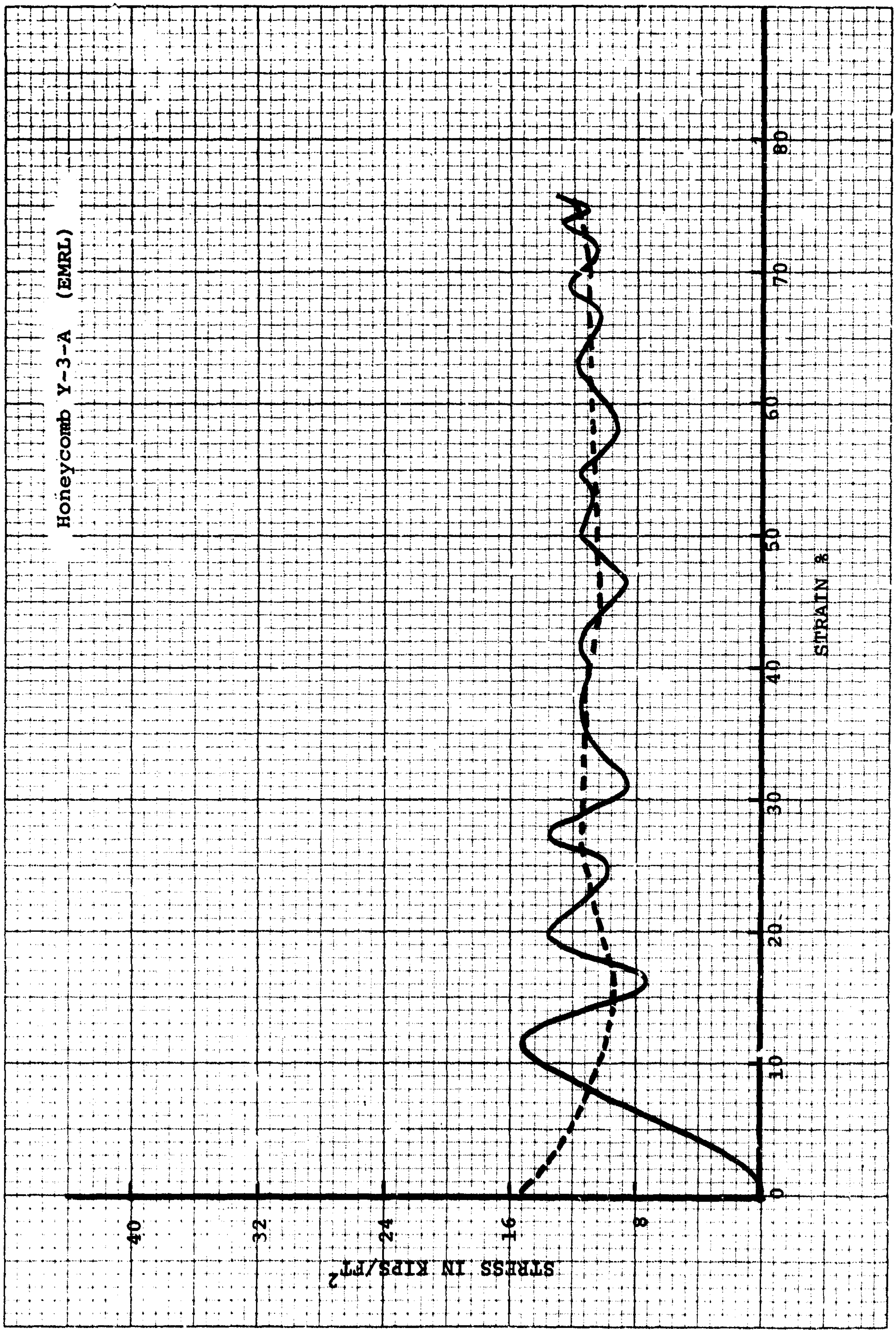

Honeycomb Y-1-A (EMRL)
STRESS IN KIPS/FT^2
40
32
24
16
8
STRAIN %
0
10
20
30
40
50
60
70
80

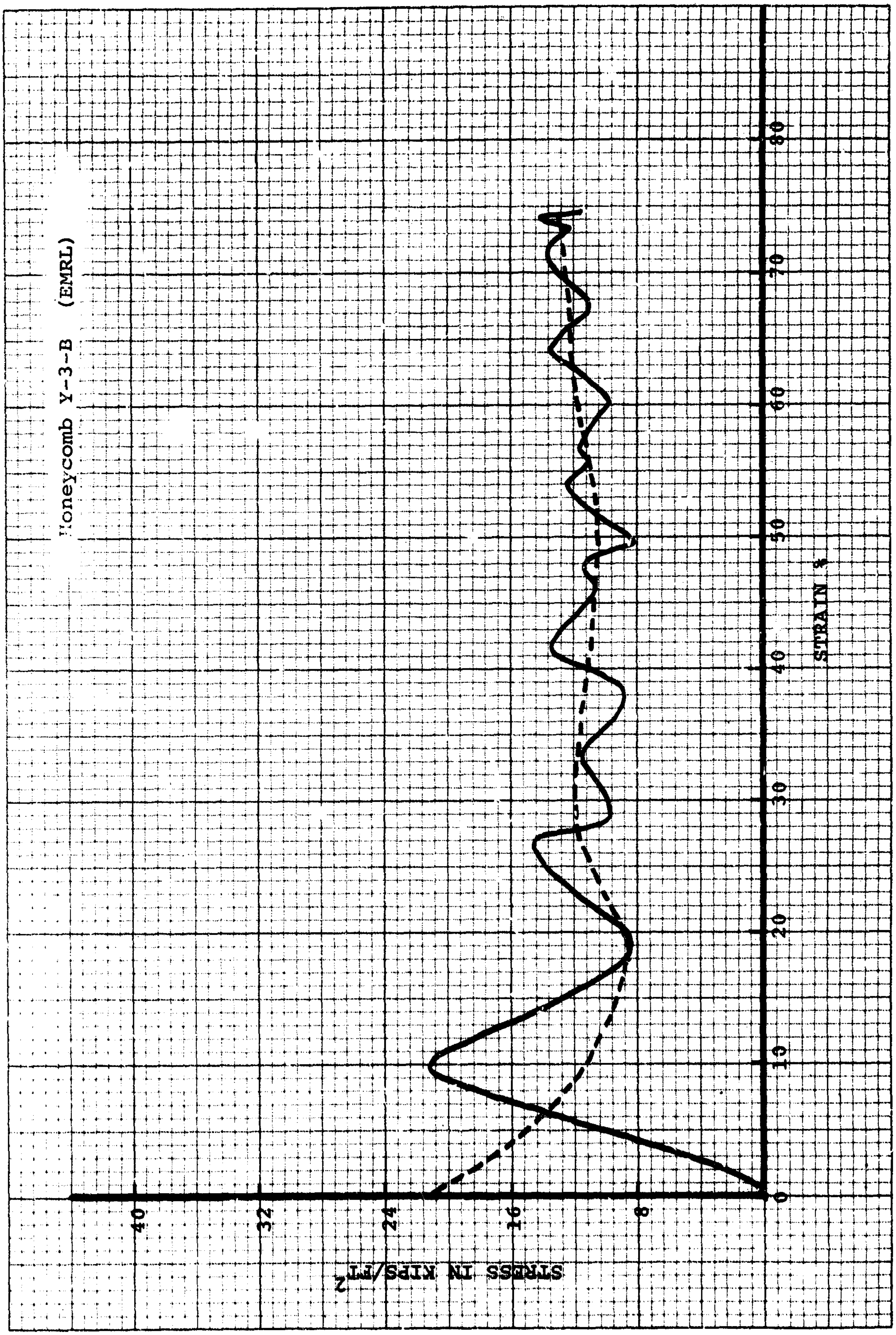

Honeycomb Y-1-B (EMRL)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT^2
8
16
24
32
40

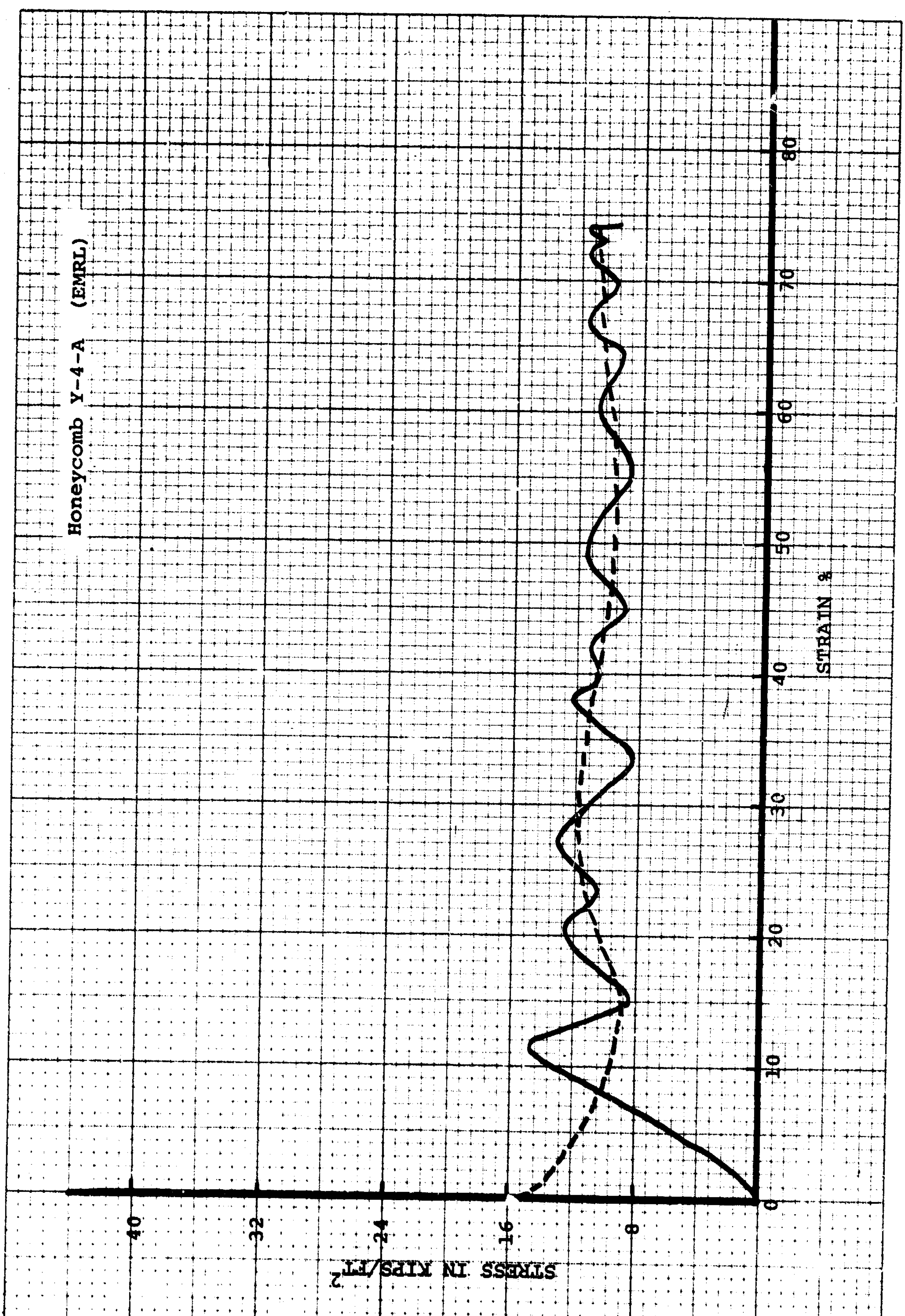
Honeycomb Y-2-A
STRESS IN KIPS/FT²
40
32
24
16
8
0
10
20
30
40
50
60
70
80
STRAIN %

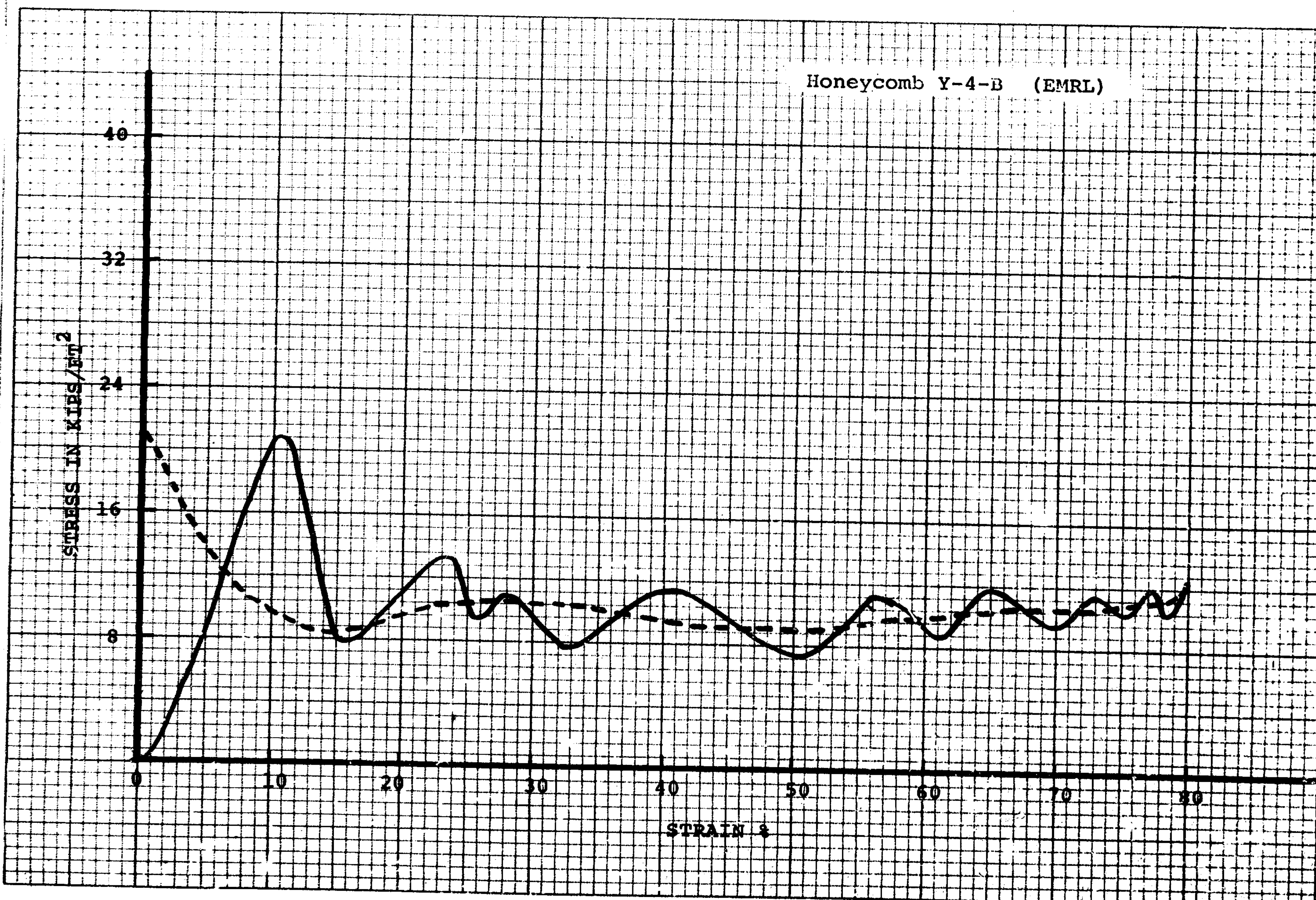


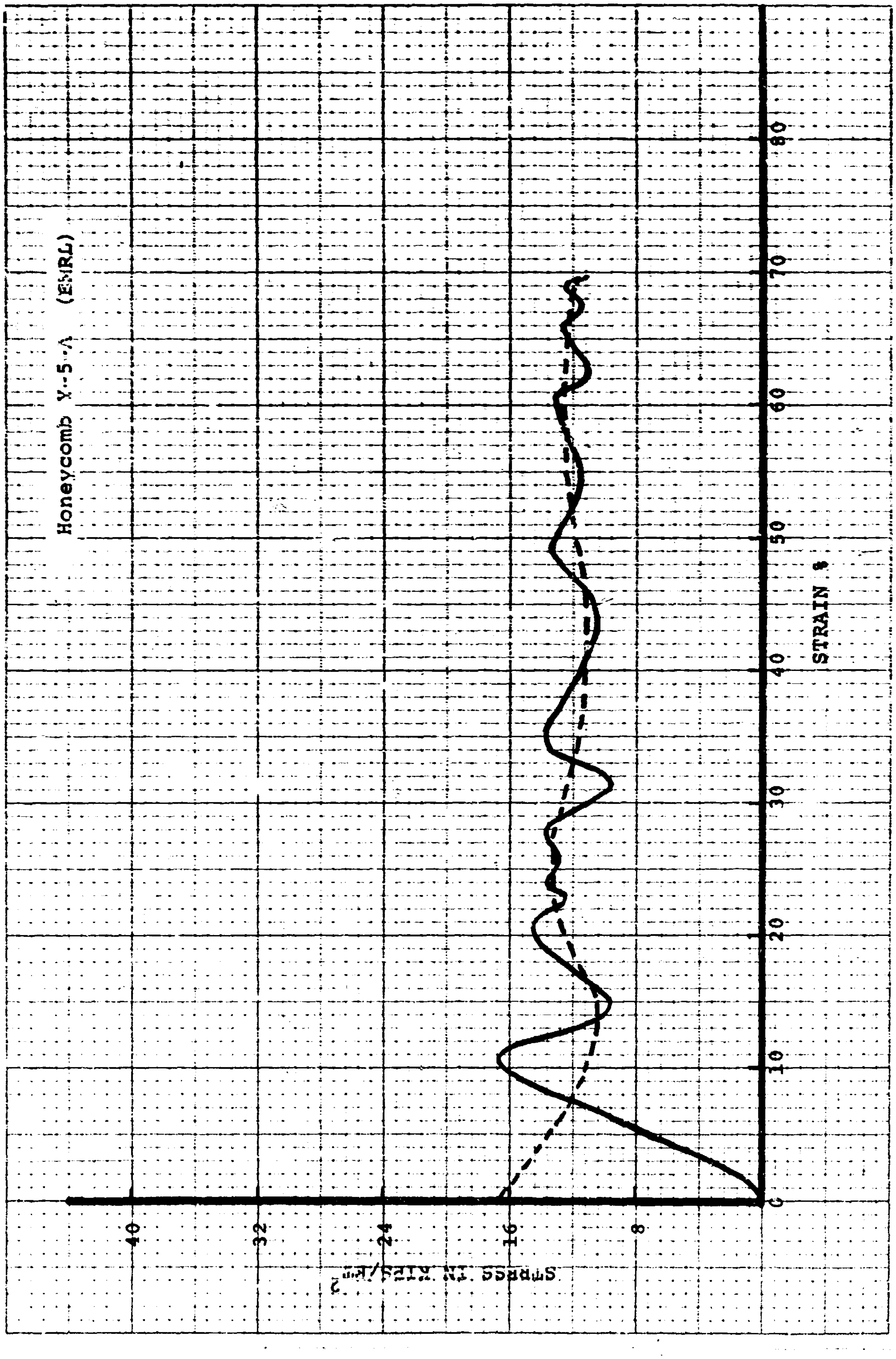
Honeycomb Y-2-B (EMRL)
STRESS IN KIPS/FT^2
STRAIN %
0
10
20
30
40
50
60
70
80
8
16
24
32
40

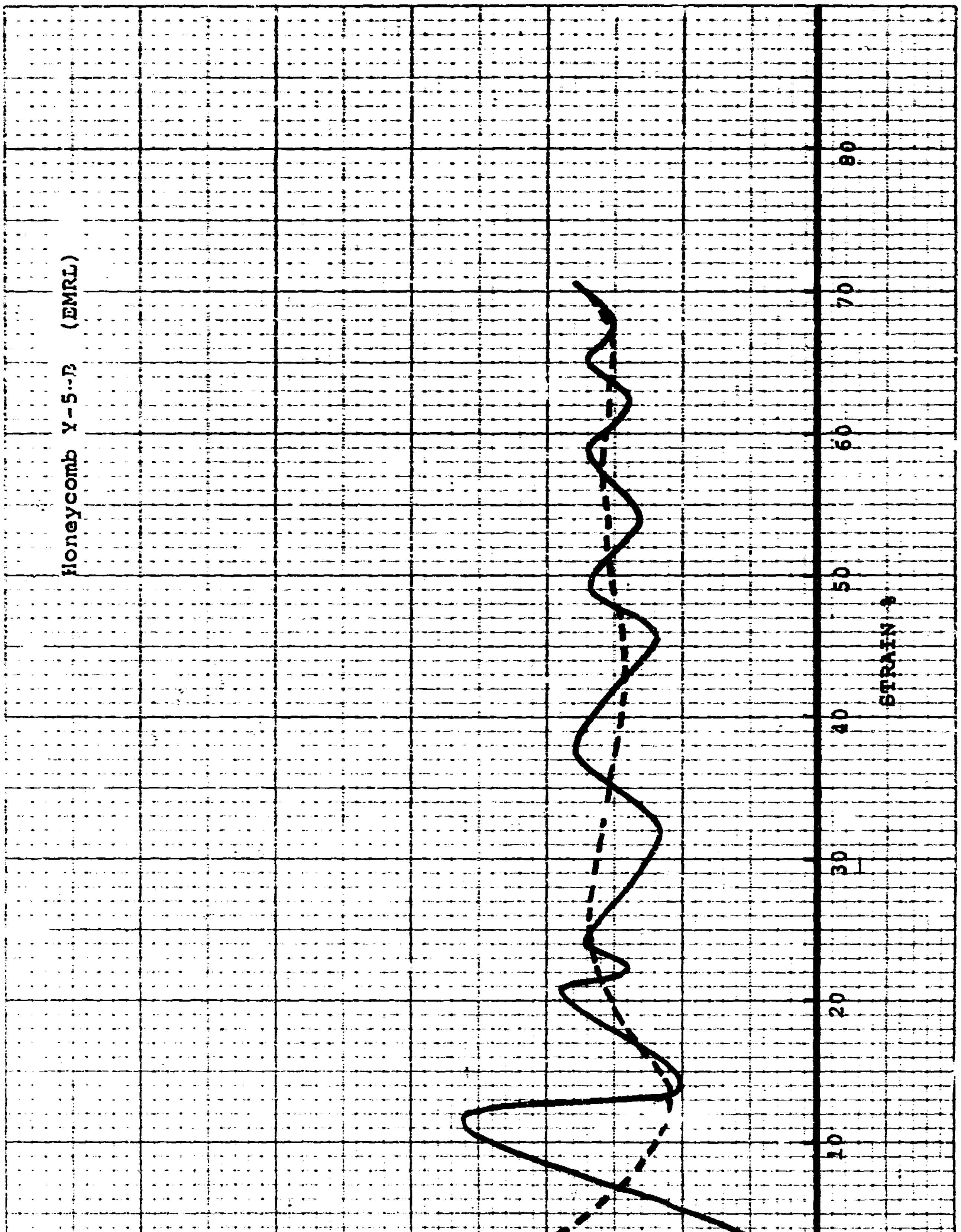

Honeycomb Y-3-A (EMRL)
STRAIN %
STRESS IN KIPS/FT2

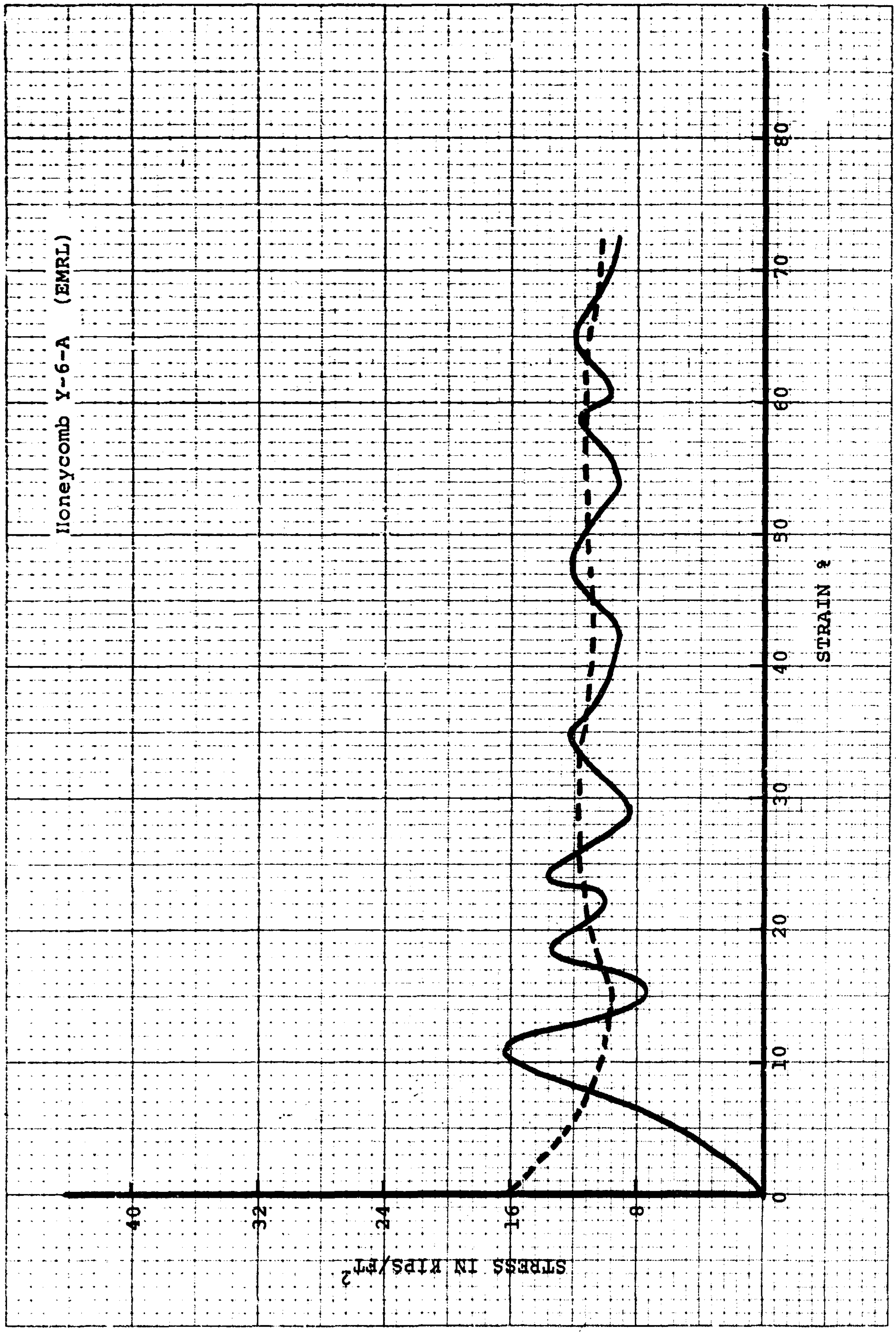

Honeycomb Y-3-B (EMRL)
STRAIN %
STRESS IN KIPS/FT²
0
10
20
30
40
50
60
70
80
8
16
24
32
40

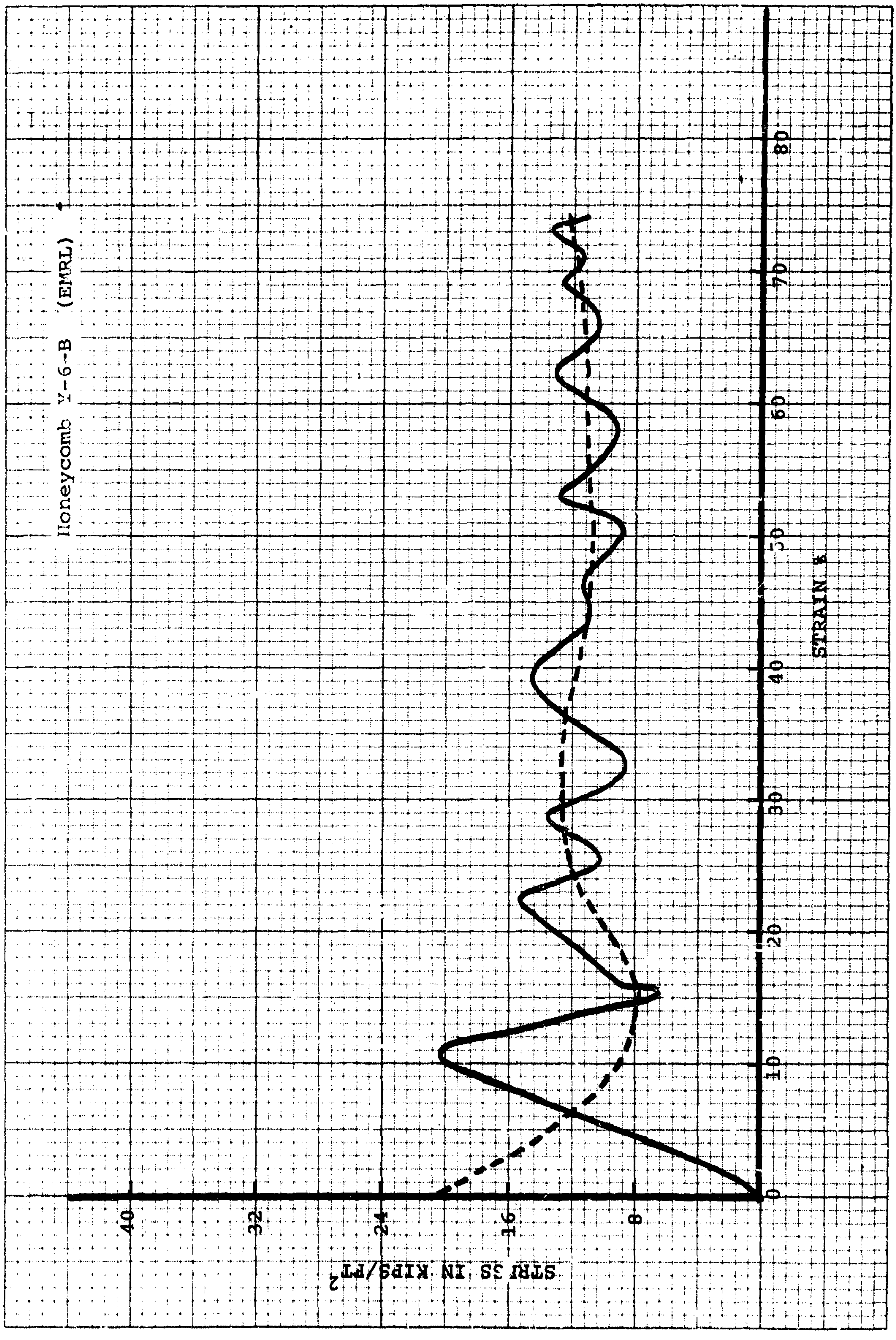

Honeycomb Y-4-A (EMRL)
STRESS IN KIPS/FT^2
40
32
24
16
8
STRAIN %
0
10
20
30
40
50
60
70
80

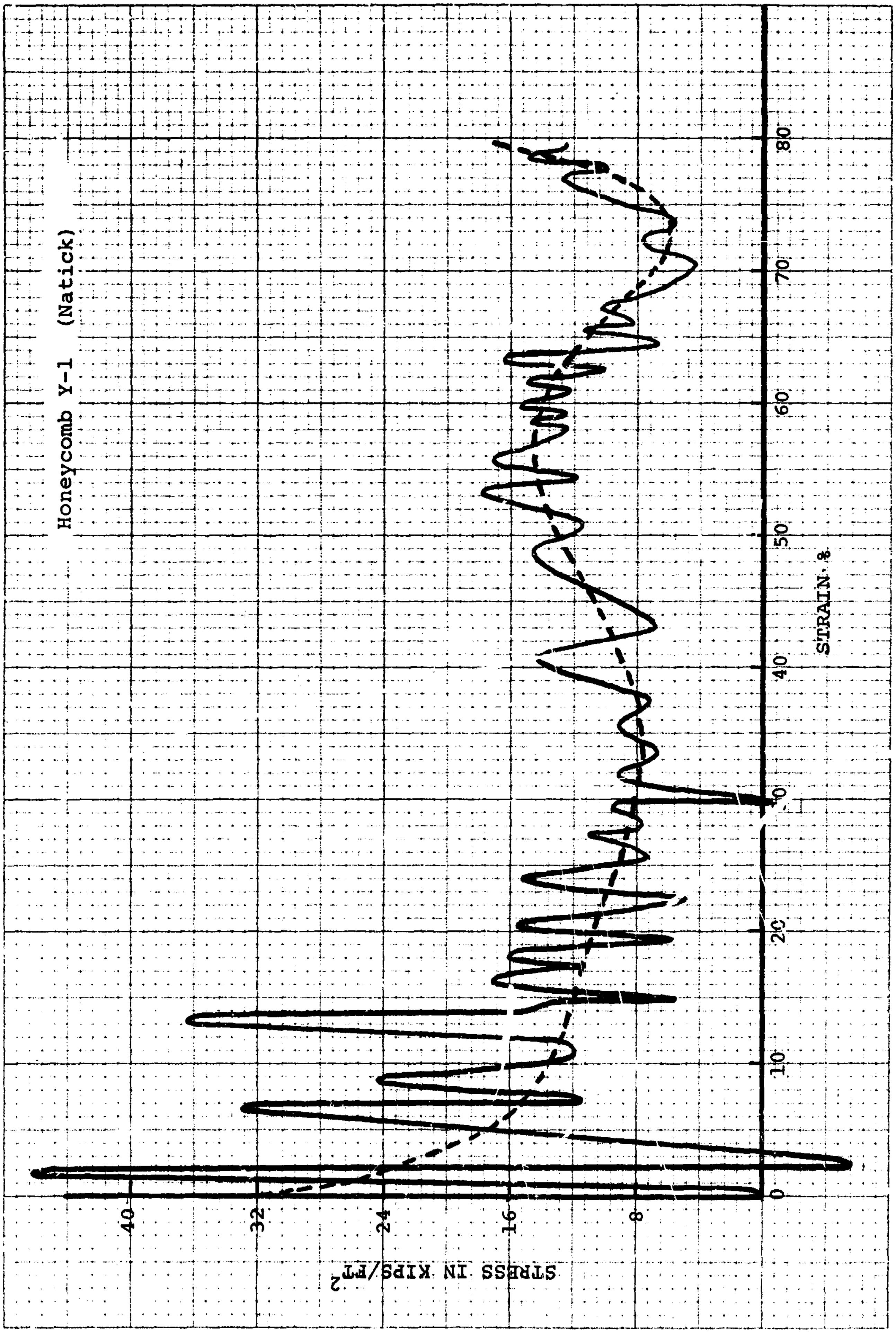

Honeycomb Y-4-B (EMRL)
STRESS IN KIPS/FT^2
40
32
24
16
8
0
10
20
30
40
50
60
70
80
STRAIN %

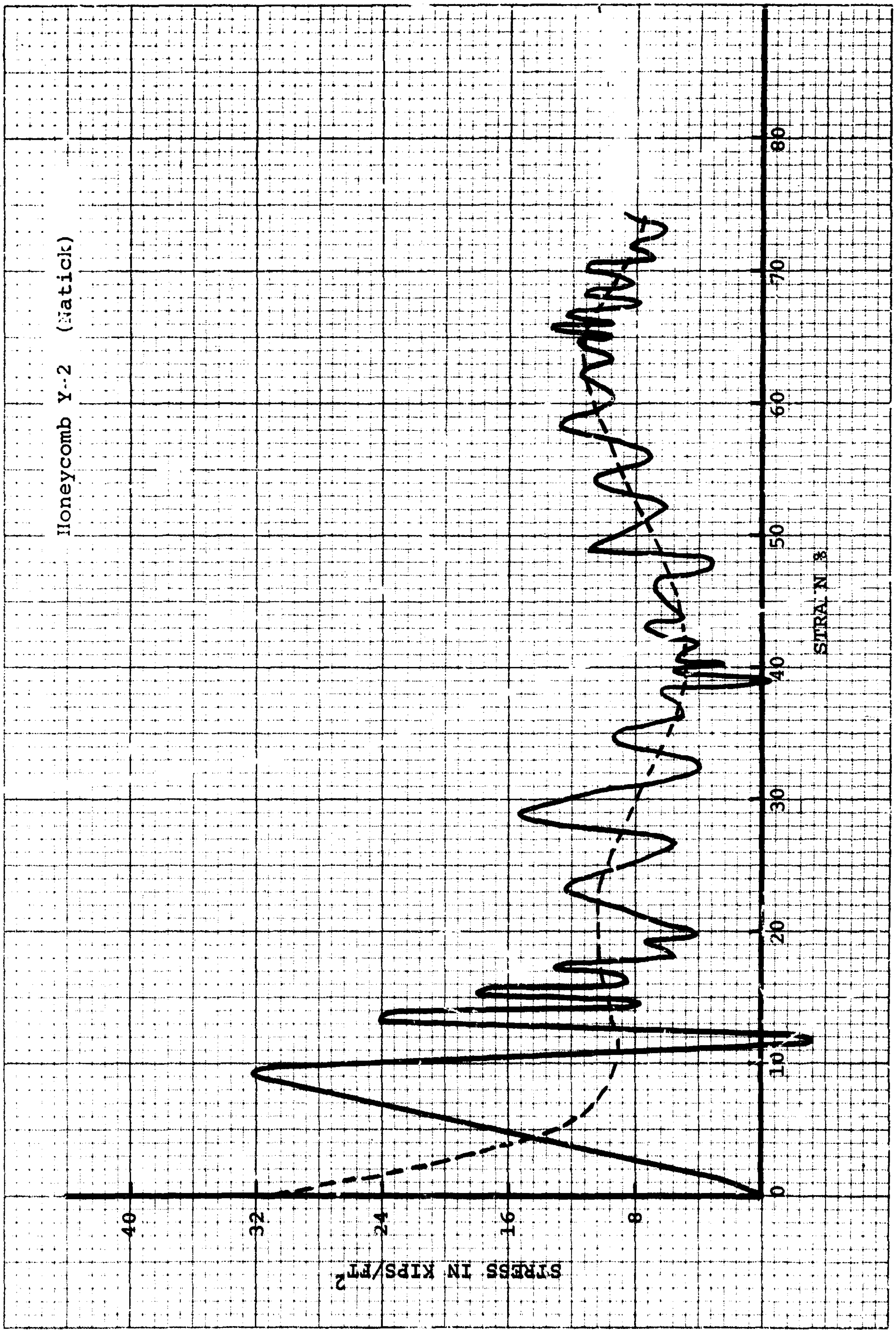

Honeycomb Y-5-A (EMRL)
STRAIN %
STRESS IN KIPS/IN^2
0
10
20
30
40
50
60
70
80
8
16
24
32
40

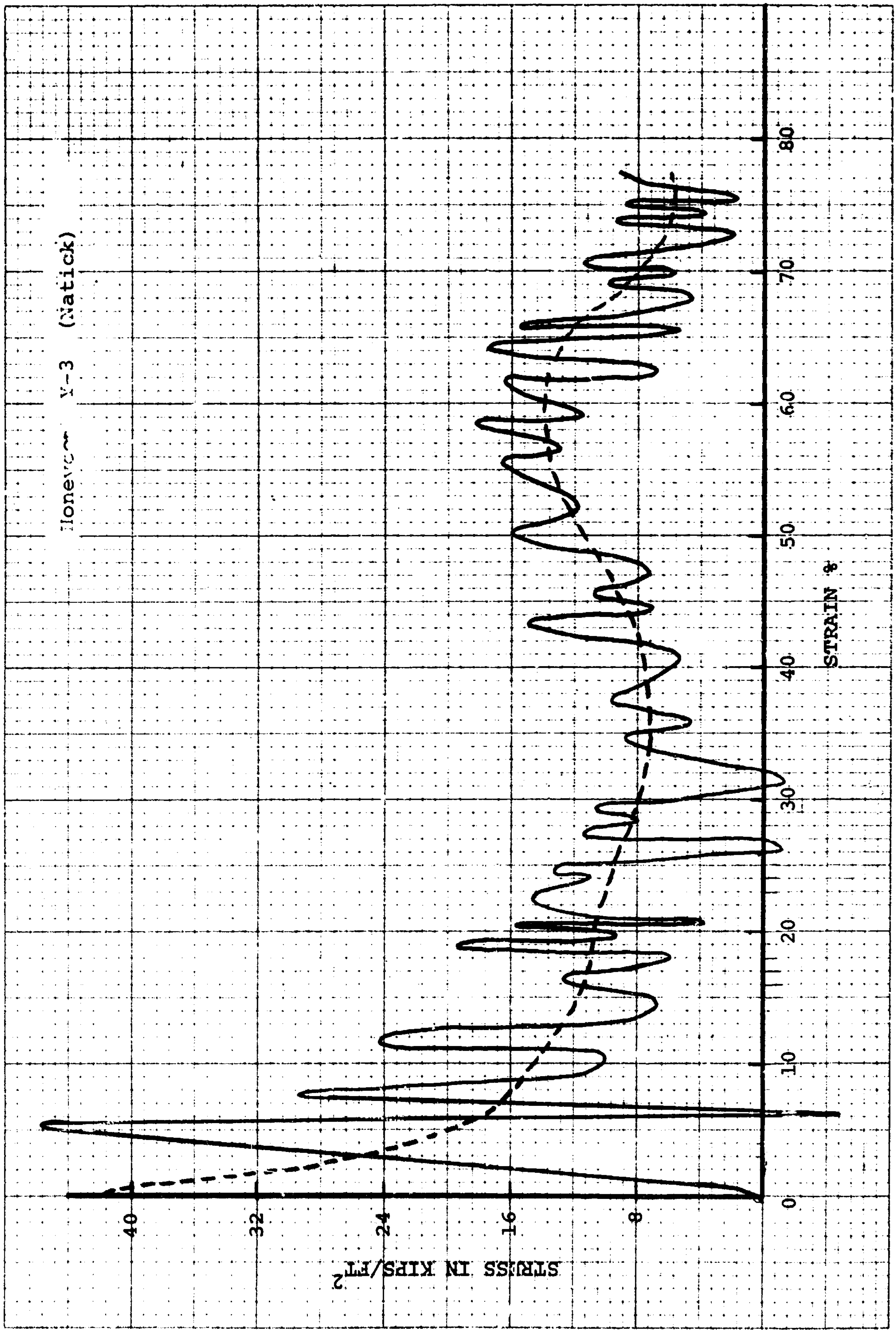

Honeycomb Y-5-B (EMRL)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT²
0
8
16
24
32
40

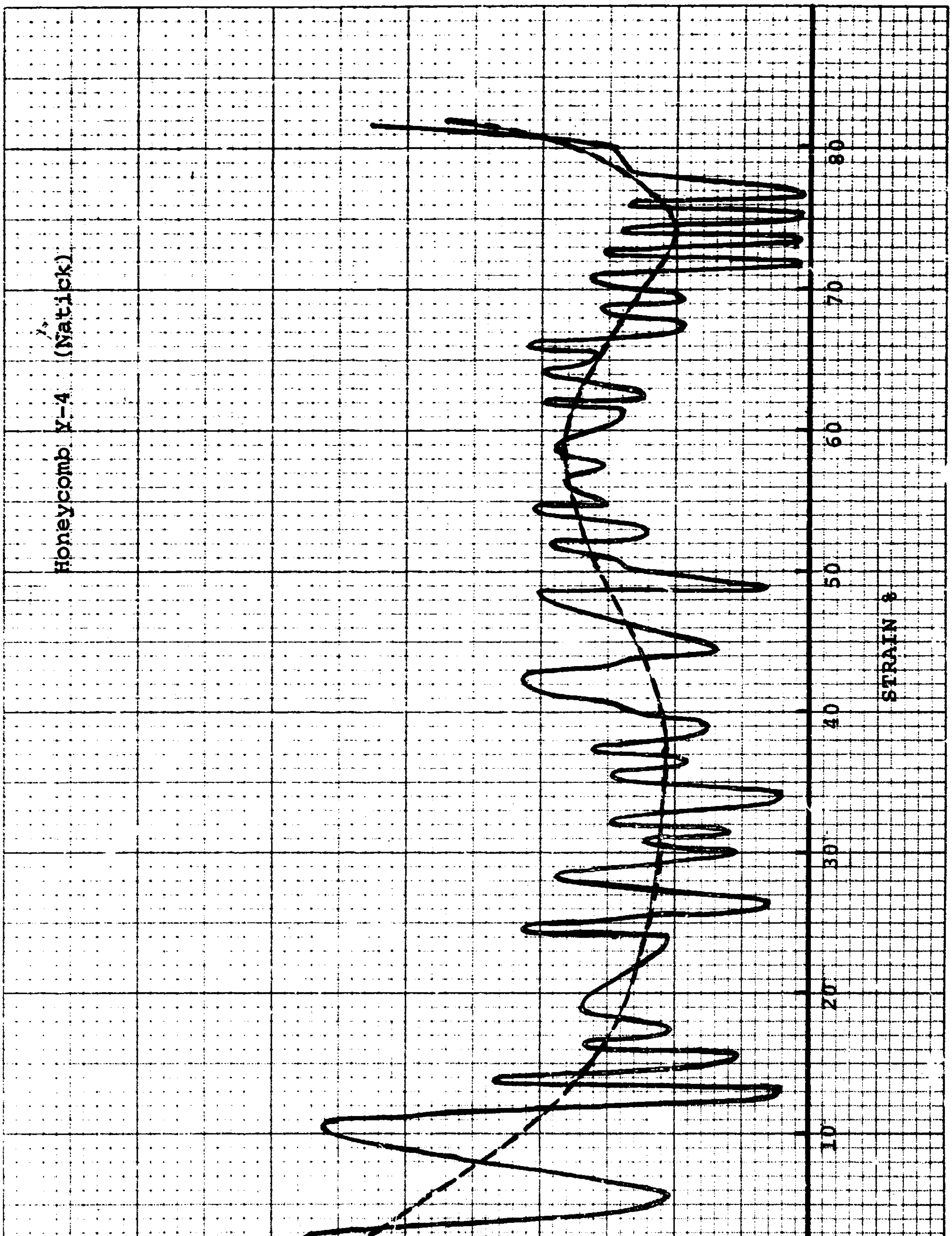

Honeycomb Y-6-A (EMRL)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT²
8
16
24
32
40


Honeycomb Y-6-B (EMRL)
STRESS IN KIPS/FT^2
STRAIN %
0
8
16
24
32
40
10
20
30
40
50
60
70
80


Honeycomb Y-1 (Natick)
STRESS IN KIPS/FT^2
40
32
24
16
8
0
10
20
30
40
50
60
70
80
STRAIN %


Honeycomb Y-2 (Natick)
STRESS IN KIPS/FT^2
40
32
24
16
8
0
10
20
30
40
50
60
70
80
STRAIN %


Y-3
(Natick)
STRAIN %
STRESS IN KIPS/FT^2
0
10
20
30
40
50
60
70
80
8
16
24
32
40


Honeycomb Y-4 (Natick)
STRAIN %
STRESS IN KIPS/FT²
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8
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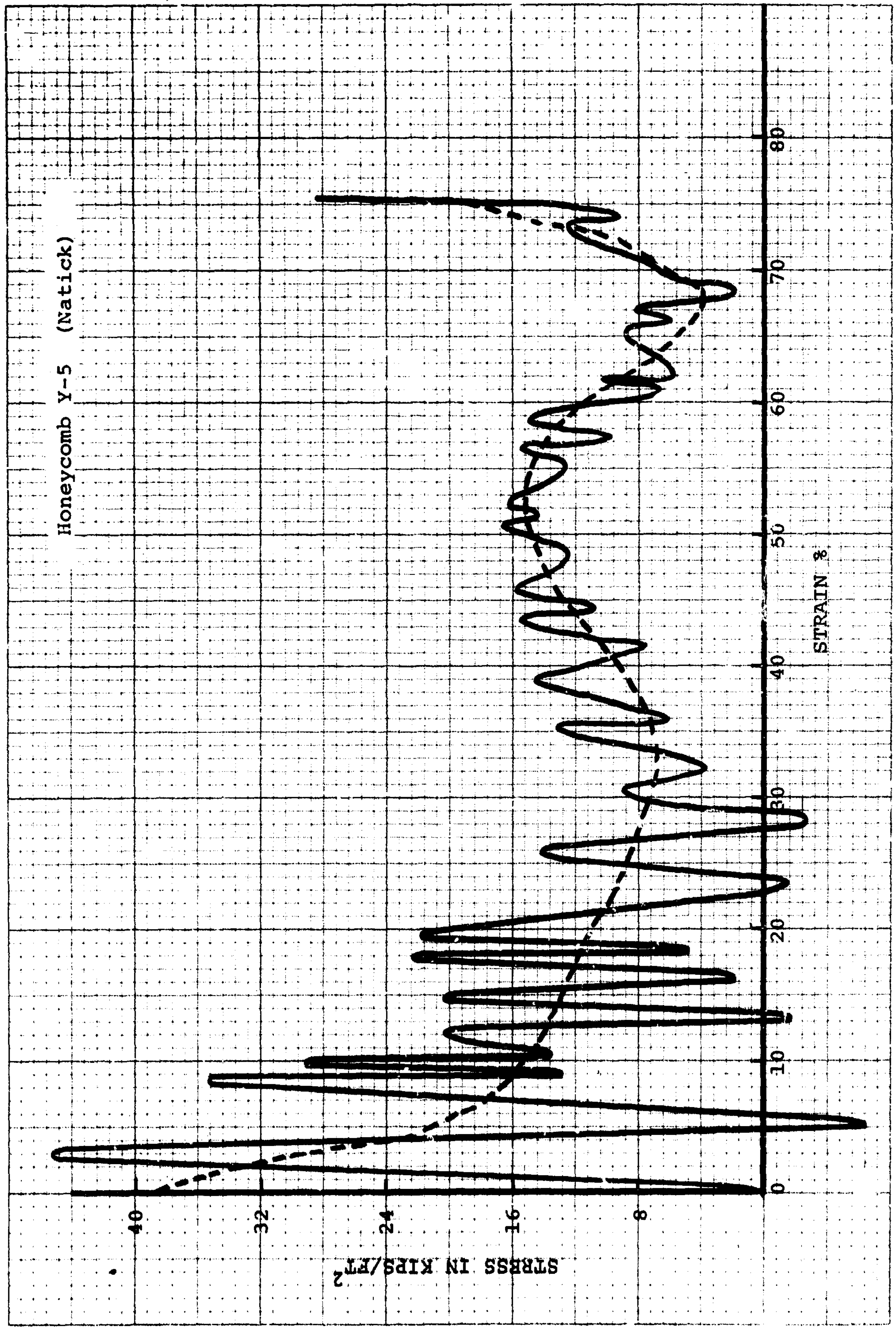
24
32
40


Honeycomb Y-5 (Natick)
STRAIN %
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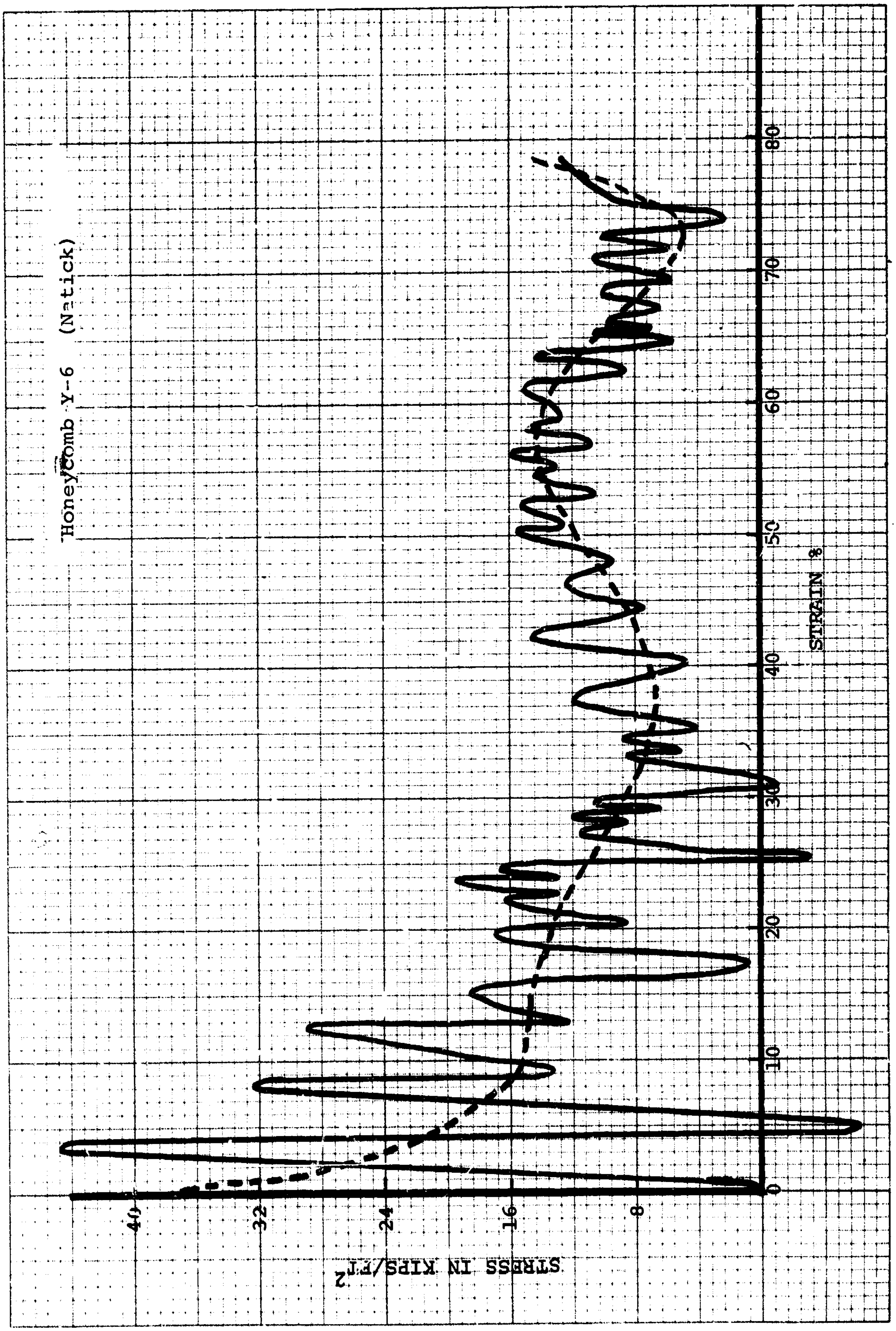
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT²
8
16
24
32
40


Honeycomb Y-6 (Natick)
STRAIN %
0
10
20
30
40
50
60
70
80
STRESS IN KIPS/FT2
8
16
24
32
40

AD ______________ Accession No. ______________

Engineering Mechanics Research Laboratory
The University of Texas, Austin, Texas

Comparative Evaluation of Paper Honeycomb Testing
W.L. Guyton, Garland Spretz and E.A. Ripperger

March 1967, 86 pp, figures
(Contract DA 19-129-AMC-582(N)
Project No. 1M121401D195
Unclassified Technical Report

Results of honeycomb tests performed in the Engineering Mechanics Research Laboratory are compared with the results of tests performed at Natick Laboratories on comparison samples. Two materials, one with a crushing strength of approximately 6300 psf, and the other with a strength of approximately 12,000 psf were included in the program. The data from both the Natick tests and the EMRL tests were evaluated using a hand smoothing procedure and a computerized mathematical curve fitting procedure. Standard deviations for sample results reduced by the latter method are consistently larger than those reduced by the former method. In general, the latter method is preferable, however, because of its greater objectivity. Methods for inferring from sample tests, the properties of an entire shipment, are discussed.

Unclassified

1. Aerial Delivery of Equipment

2. Contract DA 19-129-AMC-582(N)

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3. REPORT TITLE

COMPARATIVE EVALUATION OF PAPER HONEYCOMB TESTING

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Test

5. AUTHOR(S) (Last name, first name, initial)

Guyton, W. L., Spretz, Garland; and Ripperger, E. A.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
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8a. CONTRACT OR GRANT NO. DA19-129-AMC-582(N)	9a. ORIGINATOR'S REPORT NUMBER(S) 68-52-AD
b. PROJECT NO. 1M121401D195	
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Results of honeycomb tests performed in the Engineering Mechanics Research Laboratory are compared with the results of tests performed at Natick Laboratories on comparison samples. Two materials, one with a crushing strength of approximately 6300 psf, and the other with a strength of approximately 12,000 psf were included in the program. The data from both the Natick tests and the EMRL tests were evaluated using a hand smoothing procedure and a computerized mathematical curve fitting procedure. Standard deviations for sample results reduced by the latter method are consistently larger than those reduced by the former method. In general, the latter method is preferable, however, because of its greater objectivity. Methods for inferring from sample tests, the properties of an entire shipment, are discussed.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Test methods	8					
Test equipment	8					
Honeycomb construction	9					
Cushioning	9					
Air-drop operations	4					

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